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AGARD REPORT No.770

AGARD/SMP Review Damage Tolerance for Engine Structures 3. Component Behaviour and Life Management

(Revue AGARD/SMP — Tolérance aux Dommages pour les Composants de Moteurs 3. Le Comportement des Composants et la Gestion de Leur Durée de Vie)

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(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

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Papers presented at the 68th Meeting of the Structures and Materials Panel of AGARD in Ottawa, Canada, 23rd—28th April 1989.

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Preface

Most current military and civil engines are operated under "Safe-life" procedures for their critical components. Experience has shown that this philosophy presents two drawbacks:

(a) The move towards designs allowing higher operational stresses, and the use of advanced high-strength alloys make it likely that a disc burst could happen (following a rapid crack growth) well before the statistically-based "Safe-life" has been achieved.

(b) It is potentially wasteful of expensive components, since it has been estimated that over 80% of engine discs have ten or more low cycle fatigue lives remaining when discarded under "Safe-life" rules.

Damage Tolerance being an alternative lifing philosophy, the Sub-Committee on "Damage Tolerance Concepts for the Design of Engine Constituents" has therefore decided to conduct a series of four Workshops addressing the areas critical to Damage Tolerance design of engine parts.

The present report includes the papers presented during Workshop III which was devoted to Component Behaviour and Life Management. It also includes the content of the discussions which followed the presentations.

On behalf of the Structures and Materials panel, I would like to thank the authors, the recorders of the discussions and the session chairmen whose participation has contributed so greatly to the success of the Workshop.

Préface

La totalité des moteurs civils et la plupart des moteurs militaires sont actuellement mis en oeuvre suivant les concepts de "Durée de vie certaine" en ce qui concerne leurs parties vitales. La pratique de cette approche a mis en évidence les deux inconvenients suivants.

(a) La tendance à l'utilisation des moteurs sous contraintes mécaniques plus élevées et l'emploi d'alliages à haute résistance rendent possible l'éclatement d'un disque (à la suite d'une progression rapide de fissure) avant que la "Durée de vie certaine", évaluée statistiquement, ait été atteinte.

(b) On observe également un gaspillage de pièces onéreuses, puisqu'on estime que 80% environ des disques retirés du service conformément aux règles de "Durée de vie certaine" ont encore un potentiel supérieur a dix durées de vie en fatigue oligocyclique.

La Tolérance aux Dommages constituant une autre approche possible de la définition des potentiels de vie, le Sous-Comité "Concepts de Tolérance aux Dommages pour le Dimensionnement des Composants de Moteurs" a décidé d'organiser une série de quatre Réunions de Travail consacres aux divers aspects de la Tolérance aux Dommages appliquée aux moteurs.

Le présent rapport contient les diverses présentations effectuées à l'occasion du troisième d'entr'eux traitant du Comportement des Composants et la Gestion de Leur Durée de Vie. On y trouve également un compte-rendu des discussions qui ont suivi les diverses présentations.

Au nom de la Commission Structures et Matériaux, je remercie les auteurs, les rapporteurs de discussion et les présidents de sessions qui ont grandement contribué au succès de cette Réunion de Travail.

R.Labourdette
Chairman
Sub-Committee on Damage Tolerance Concepts
for the Design of Engine Constituents

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The Panel wishes to express its thanks to the AGARD Canadian National Delegates for the invitation to hold this Meeting in Canada.

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AGARD DAMAGE TOLERANCE CONCEPTS FOR ENGINE STRUCTURES
WORKSHOP III – COMPONENT BEHAVIOUR AND LIFE MANAGEMENT

by

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1. Introduction

This third AGARD workshop on damage tolerance concepts for gas turbines considers how the specific needs of the component can be taken into account, how the type of mission flown affects the approach taken, the role of in flight monitoring and life management planning. These considerations are required to produce positive life and integrity statements from an understanding of the component condition gained using the inspection techniques discussed in workshop I, and our fundamental knowledge of materials and defect behaviour covered in Workshop II.

Components in service engines behave differently from laboratory specimens of the same material (even when cut from the components concerned) for the following reasons.

a) The component stress/strain/time/temperature operating envelope is insufficiently well defined.

b) The multi-axial stress/strain conditions created by the geometry of the component features are insufficiently understood.

c) The missions flown deviate from those considered in the component life analysis either due to complexity that cannot be covered by the techniques available or to the engine being flown through missions that were not initially envisaged.

d) Changes due to time or environment invalidate the initial assumptions of component condition and behaviour eg. material instability, oxidation and corrosion.

e) Surface damage occurs, eg. fitting damage, frettage, foreign object damage, invalidating the assumptions regarding initial material condition.

f) Uncertainties in the initial assumptions promote unpredicted behaviour eg:

- presence of undetected sub-surface defects.
- unknown synergistic effects between single failure modes (creep/fatigue interactions).
- presence of residual stresses.

These uncertainties have been accounted for so far by validating designs by:

a) component testing under "representative" conditions.

b) accelerated mission testing of bench engines.

c) Regular inspection of critical parts in the engine.

d) Regular withdrawal of fleet life-leading components at part life for detailed inspection.

e) In-flight monitoring of engine performance and condition.

Above all the use of forgiving materials, within a limited performance envelope and with large "safety" factors, has, in the main, avoided failures due to our lack of knowledge of materials and component behaviour.

The demands for higher performance engines of lower weight and longer life, all at lower cost, are forcing the designer to eat into these margins hence the need to reduce the degree of uncertainty in the knowledge of materials, component and engine behaviour.

2. Current uncertainties and short comings

The shortcomings of current design/evaluation systems vary in detail from component but some general themes emerge:-

a) Initial evaluation model of component

This nowadays tends to be a two dimensional or three dimensional elastic finite element model which is used to calculate stresses and deflections at features and in plane sections.

The component however behaves as a three dimensional, plastic, time-dependant entity, especially at features. Factors such as creep and plastic deformation are becoming important in components such as discs where fatigue was considered dominant. Cyclic behaviour, especially thermal fatigue, is important in thermal stressed components such as turbine blades and combustors where creep ruled supreme (Fig 1).

b) Component failure criteria

Some general concept of the presence of an "engineering crack" has been taken as an indication that a component should be taken out of service for replacement or repair before catastrophic failure occurred which would prejudice the safety of the aircraft. Even where component and engine testing have taken place these have rarely been taken to catastrophic failure - leading to a lack of knowledge of failure modes and the integrity of cracked parts (Fig 2). The margins expected from in-service experience have been eroded by the increasingly high performance expected in new designs. These stress levels have promoted new failure modes for the cracked condition leaving greatly reduced in-service life margins. In addition the increasing move to mixed mode conditions, leads to uncertainties about damage accumulation and ultimate failure. This is particularly seen in cooled turbine blades and circumferential slot compressor disc rims operating in the creep regime.

c) Mission analysis

Whilst the maximum conditions can be limited by maximum thrust ratings and restrictions on speed of acceleration, the number and size of the minor excursions within a mission, which are having an increasing major effect on life and integrity, cannot be predicted - especially for fighter aircraft (Fig 3).

Arbitrary exchange rates of x cycles/hour with an expression of life in flying hours is either unacceptably pessimistic on component life or will lead to some in-service failures within a fleet due to the engine to engine variation.

d) Changes due to time and environment

With relatively low component lives (up to 1000 hours) normally associated with military aircraft the major long term problem seen with components has been the rusting of steel! - especially bearings and shafts (Fig 4). Even in these cases much of the problem has been cosmetic as the pitting produced did not cause failure in less than the predicted component life.

This is no longer the problem as the extended times now required are outstripping the capability of the materials and coatings available. Many materials exhibit changes in the long term which degrade the design properties as well as the obvious surface difficulties caused by corrosion (Fig 5).

e) Surface damage

Current criteria and design curves are based upon the assumption that the component starts with a well machined clean surface. The existing systems do not permit allowance for surface damage created by fitting damage, fod or frettage and yet this can have a major effect on such things as disc life, blade root performance or location of critical components such as burners (Fig 6).

Current lifing systems assume that such happenings will be found and suitable palliatives applied - eg. anti-fret coatings.

f) Uncertainties in initial assumptions

These are the things that really cause failures because the current system does not make allowances for the unknown! Everything is assumed innocent until proved guilty whereas the opposite should be always assumed for critical components (Fig 7). If you can't ensure a disc is crack-free the presence of a crack must be assumed, albeit on a probabalistic basis.

This is an expensive philosophy, however, unless one recognises that inspection is not the real way of avoiding the presence of defects that will cause failure.

Most of these difficulties have been dealt with in the past by either rig testing components or bench testing engines to evaluate their behaviour under 'real' conditions. Because of constraints of time and money however the 'real' test conditions have over the years departed from reality:-

a) by moving to accelerated testing eliminating "dwell" times from test cycles.

b) only testing at perceived "maximum" conditions and allowing for others by calculation.

c) extrapolating further from existing tests to new design conditions by calculation to limit the number of tests carried out.

d) Tests are rarely taken to failure.

This approach is increasingly challenging the validity of our understanding, models and experience. The indications are that they need continuous development to keep pace with the demands of new designs.

3. The effect of engine design trends

Gas turbines of the future are required to have higher thrust/weight ratios, lower fuel consumption, lower operating/maintenance costs and lower cost of ownership (Fig 8).

To achieve this higher required performance components are going to operate within wider envelopes of stress and temperature. This in its own right will mean that components will increasingly operate in regimes of fatigue creep and plastic strain not previously encountered or deliberately kept away from eg. creep in discs. In addition it also means the introduction of new materials of greater strength and stiffness that will be less forgiving of the manufacturing defects, damage and the changes that come about from high temperature exposure for longer times and corrosion. This ultimately will lead to use of novel materials where current component prediction methods are not applicable eg. composites and ceramics (Fig 9).

The needs for lower costs will also force the design of components for longer in-service lives based on more limited component testing. The analytical methods used to predict component behaviour will therefore become far more critical in both validating the design and interpreting the component tests carried out.

The higher performance and longer lives demanded of the components will also make them more susceptable to variations in the missions flown and the environmental effects encountered. In particular the higher temperatures that will be encountered in compressors and turbines will exacerbate current problems and introduce new ones - eg. high temperature oxidation of turbine blade superalloys and hot salt stress corrosion of titanium compressor disc rims.

4. Future Approach

To accommodate these changes we need to consider our future approach to technologies covering component behaviour and lifing management.

a) Lifing methods and behaviour models

Lifing methods and behaviour models need to become based upon an understanding of true materials behaviour in component form, using observations of component behaviour rather than empirical extropolation of previous experience. This is already happening to some extent with the introduction of 3D plastic-elastic finite element modelling allied to a detailed analysis of crack life in engine discs. There is a long way to go, however, especially in considering.

- Multiaxial loading
- Flight cycle/mission profiles
- Multiple failure criteria (creep/fatigue)
- Environmental and damage effects

b) Role of Component testing

Because of the complexity of component behaviour we are still some way off a dependable model that predicts behaviour and life from first principles. We will remain dependant upon component testing to validate our models for the regime we are evaluating and to point out errors and omissions in the findings they present to us.

This, however, is a new role for component testing which has been principally aimed at validating specific designs for defined operating conditions in the past.

This changing role will demand that more careful thought be given to the:-

- relationship of the test condition to reality.
- monitoring techniques that can evaluate the performance of material and component throughout the test.
- full analysis of the test results and failed component (failure must occur if the test is to really mean anything).
- Use of the test results based upon a fundamental understanding of component behaviour in engines ie. to calibrate the scientifically derived models.

c) Role of engine accelerated mission testing

This performs a similar role to component testing, to be used when appropriate test conditions can only be achieved by running components in engines. This is especially true when vibration and rapid temperature changes are involved - but engine testing is always less exact, more costly and more difficult to monitor than similar rig testing.

It is also easy to assume that, because the test involves engine running, it must be more accurate. The relationship of engine testing to real flight conditions is complex in the extreme. If useful information is to come from this type of testing much thought should be given to analysis of the results.

d) On-condition flight monitoring

In flight monitoring is becoming more essential for three reasons:

- validation of the flight profile and component operating envelopes to assess the validity of the analysis assumptions.
- monitoring of in flight behaviour of the engine to see if it performs as predicted eg. vibration monitoring, chip detectors, etc.
- measurement of engine usage - 'cycle counting'.

The importance of ensuring that the engine behaves in the manner predicted is self evident - the predictive technology we have is not good enough to be relied upon without continuous validation at this stage in its development.

The necessity of recording the actual flying carried out is inversely proportional to the degree to which the pilot flies a set mission profile. Even on civil aircraft this is becoming increasingly difficult as the airlines wish to minimise fuel burn and take credit for reduced engine operations. On military aircraft flight recording is the only way we will be able to assess life with any degree of accuracy.

e) Life Management Planning

Most important of all is the need for a plan to manage life and integrity from validation of the design model and assumptions through to monitoring of the weaknesses and uncertainties by in-service inspection. This life management planning will allow a continuous reassessment of component life and integrity as data becomes available concerning its behaviour in service. This offers the best warranty against premature failure there is - and allows proper logistic and financial planning of engine overhauls and component replacements.

Conclusions

This workshop covers the critical technologies that relate the science of materials and defect behaviour, and the knowledge of component quality, to the reality of component performance in the engine. The initial predictions of life and integrity, even using todays complex models and super computing methodology, is relatively cheap. The validation of these models by component testing and engine accelerated mission testing is expensive. The inevitable move to less validation testing must be balanced by appropriate in service planning and monitoring. This workshop should allow the balance of these to be assessed at todays level of capability.

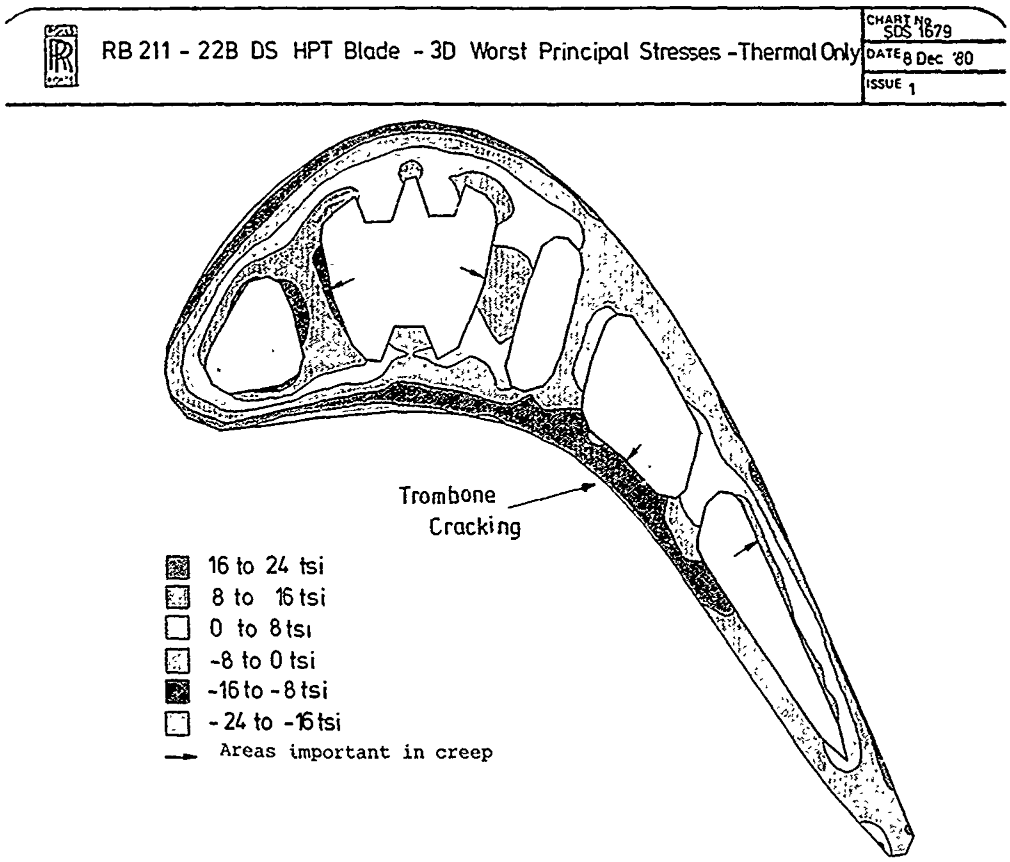

Fig 1 - FE model of blade showing area where creep is important.

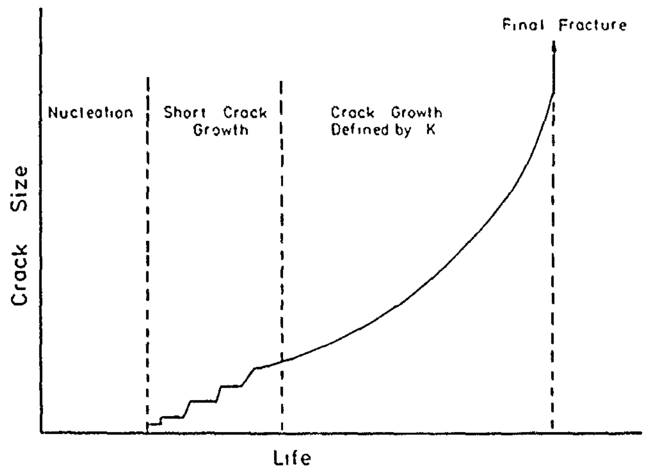

Fig 2 - Stages of Cyclic Life.

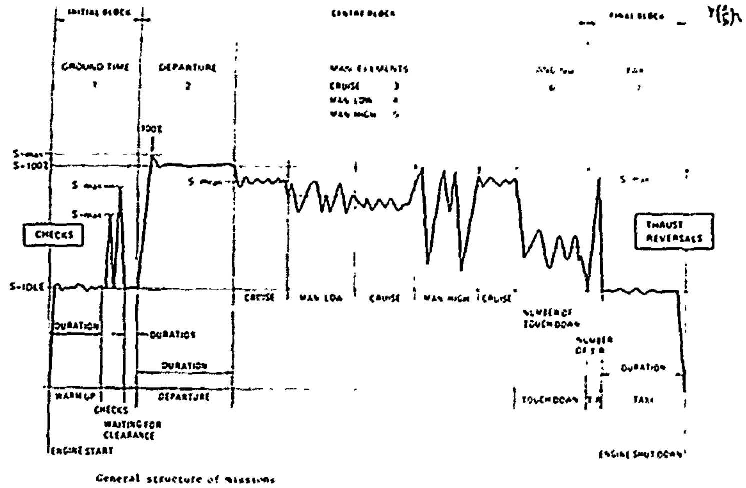

Fig 3 - Fighter typical mission profile.

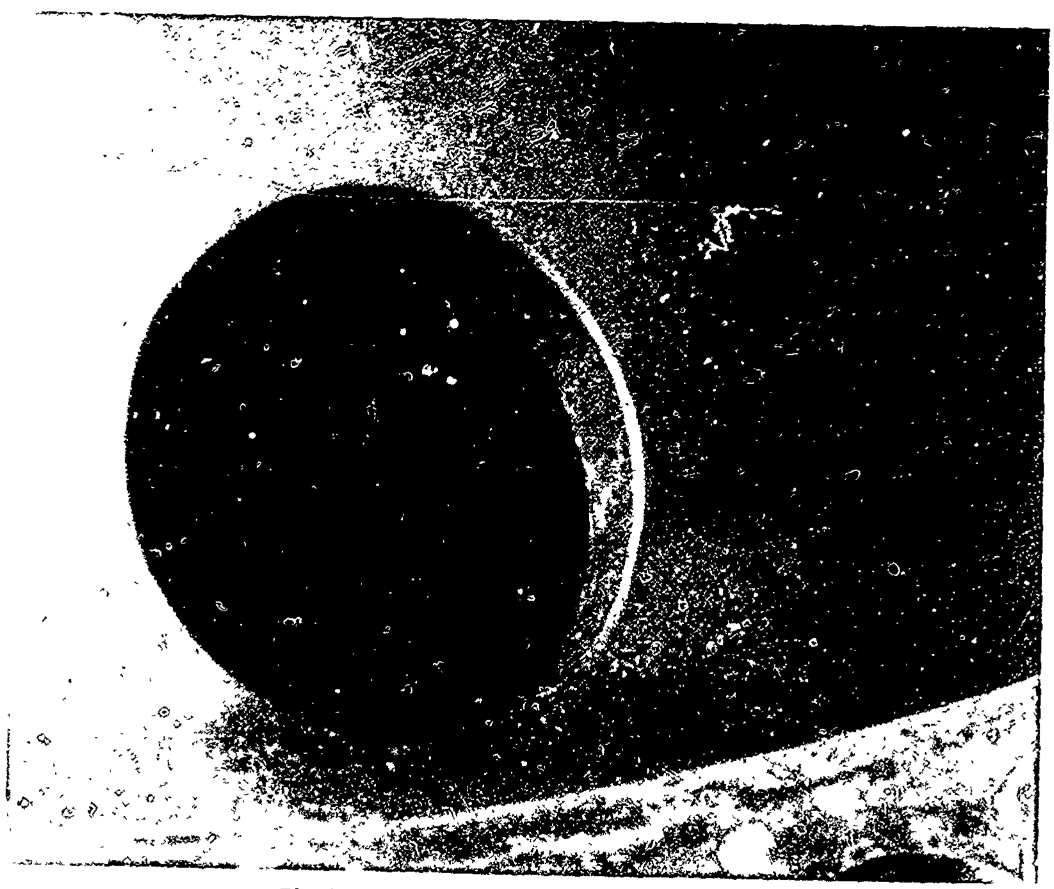

Fig 4 - Corrosion pits on shaft.

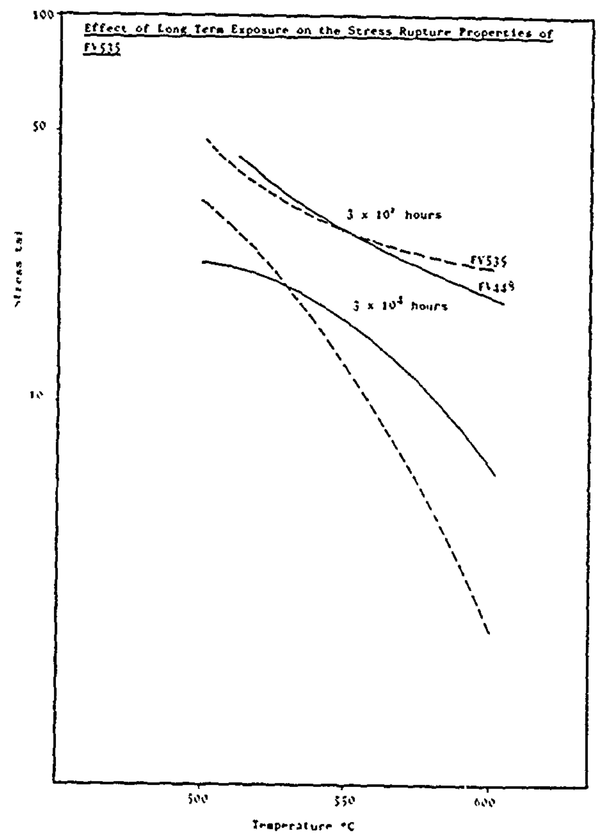

Fig 5 - Creep curve of FV535 showing deteriation with time of exposure compared to FV448

Fig 6 - Surface damage leading to failure.

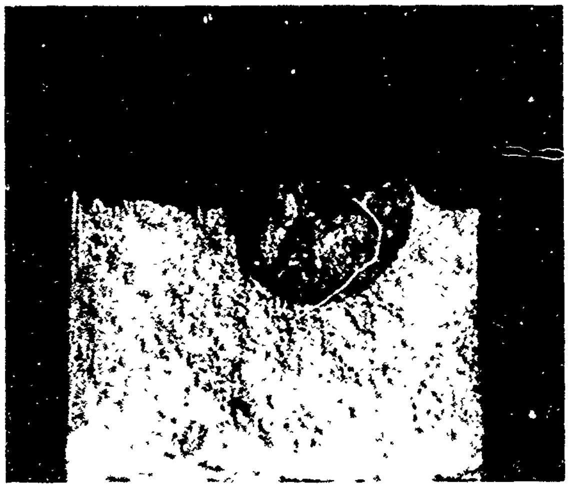

Fig 7 - Disc burst from subsurface failure.

Future military engine using new materials and process technology

Targets relative to current rechnology

- Thrust/weight 20:1
- Reduction in mission fuel burn by 25 per cent
- Reduction in first cost by 25 per cent
- Maintenance costs reduced by 25 per cent
- Stoichiometric burning — corresponds to turbine entry temperature of approximately 2,500°K
- Design life — 5,000 cycles

Aim is to achieve 50 per cent by improved design and 50 per cent by improved materials

Fig 8 - Advanced fighter engine targets.

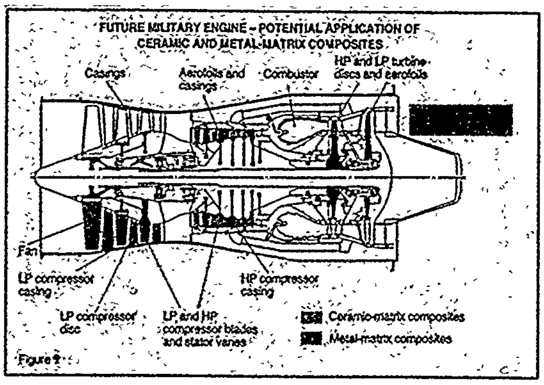

Fig 9 - New materials in engines.

CALCUL DE DUREE DE VIE DES COMPOSANTS DE TURBOMACHINES

par

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RESUME

Aujourd'hui, la réalisation de turbomachines à hautes performances nécessite, compte tenu des températures et niveaux de chargements envisagés, de disposer pour les pièces moteur les plus sollicitées, de méthodes de prévision de durée de vie, capables de prendre en compte tous les modes d'endommagement observés sur les matériaux utilisés aux températures considérées.

Pour cela, la SNECMA utilise des approches permettant de suivre les évolutions temporelles du comportement et de l'endommagement, qui résultent des sollicitations multiaxiales thermomécaniques et cycliques rencontrées par les matériaux constituant les structures.

Dans cet exposé, on se propose de présenter quelques applications des divers concepts de durée de vie à initiation ou en propagation de fissure.

1 - INTRODUCTION

Tout au long de ces vingt dernières années, l'amélioration constante des performances thermodynamiques des turbomachines, s'est traduite par une augmentation non moins constante des températures d'entrée turbine et des taux de compression, avec comme incidence directe un accroissement des efforts supportés par les composants moteur. Le développement considérable des superalliages base nickel et des alliages de titane à très hautes résistances mécaniques, associé à l'affinement des méthodes de calcul, a permis d'augmenter notablement le niveau de sollicitation thermomécanique, afin d'atteindre les objectifs de masse recherchés et de répondre aux demandes de performances accrues pour les nouveaux projets.

Parmi ces structures, certaines comme les disques, font l'objet d'une attention particulière car leur intégrité est vitale pour la sécurité de l'avion. Les niveaux de températures auxquels ils peuvent être soumis ainsi que les variations de contraintes thermomécaniques qu'ils subissent suite aux variations de régime du moteur (voir figure 1), sont de nature à engendrer des processus d'endommagement conduisant à l'initiation de fissures puis à leur propagation jusqu'à une taille pouvant entraîner la rupture des disques.

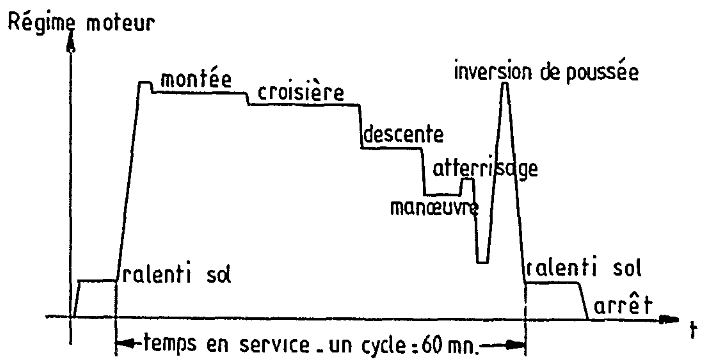


Figure 1 : Cycle de vol typique pour turboréacteur civil

Les concepteurs définissent des géométries où des zones de plus en plus importantes des disques sont soumises cycliquement, à faible fréquence, à des niveaux de contrainte dépassant la limite d'élasticité du matériau : il s'ensuit par définition une dégradation par des phénomènes de fatigue oligocyclique. L'objet de cet exposé est de présenter les divers modes d'endommagement et la façon dont la SNECMA tout particulièrement aborde ces problèmes.

A cet effet, la SNECMA utilise les méthodes basées sur des modèles sophistiqués de comportement viscoplastique et de cumul du dommage de fatigue et de fluage. Dérivés de l'approche thermodynamique locale des processus irréversibles dans les milieux solides [1], ces modèles ont fait leur apparition il y a une dizaine d'années. Depuis, ils font l'objet de développements très importants de la part des instituts et laboratoires de recherches

français, soutenus en celà par la SNECMA. Aujourd'hui, ces modèles ont atteint une certaine maturité et permettent de décrire de façon satisfaisante la plupart des effets observés sur les matériaux fortement sollicités en fatigue à haute température.

2 - CRITERES DE PREVISION DE DUREE DE VIE

2.1 - ENDOMMAGEMENT OBSERVE EN SERVICE

Ainsi que cela a déjà été mentionné, l'endommagement dans un disque est principalement dû à la succession de cycles "marche-arrêt" du moteur, sources de contraintes de forte amplitude et de faible fréquence ; par définition, il s'agit d'un phénomène de fatigue oligocyclique. Néanmoins, il vient se superposer des effets inhérents au fonctionnement du moteur qui amplifient considérablement l'endommagement en fatigue oligocyclique, et peuvent, dans une certaine mesure, modifier les critères d'amorçage de fissures en fatigue :

- interaction fatigue-fluage et plus généralement, effets de l'environnement, dûs à des temps de maintien sous une contrainte proche de la charge maximale à températures élevées,
- superposition de petits cycles de faible amplitude et haute fréquence, propres à toute machine tournante,
- sollicitations anisothermes liées à la présence de champs de température évolutifs, fonctions des modes de ventilation de la machine,
- cyclage sous amplitudes variables, avec succession de cycles et de paliers de différents niveaux, surtout observés sur moteurs militaires.

2.2 - LES DIFFERENTS STADES DE LA DUREE DE VIE

Que ce soit sur pièces ou sur éprouvettes, la durée de vie en fatigue se décompose en trois phases :

- écrouissage cyclique homogène du matériau, qui se traduit selon les cas, par une consolidation ou un adoucissement de l'alliage suivi d'une stabilisation.
- endommagement localisé, marqué en général par une déconsolidation, qui se décompose en deux périodes :
  - . amoçage de fissure (selon l'un des mécanismes précédemment décrits),
  - . propagation de la fissure,
- rupture finale.

La phase d'amorçage est globalement assimilée à celle qui précède la propagation d'une ou plusieurs fissures macrocospiques. Elle se caractérise par un endommagement qui se manifeste sous forme d'accumulation de lignes et plans de glissement, de création de cavités ou de formation de microfissures.

Dans le cas de matériaux à très haute résistance, la phase d'écrouissage cyclique peut être très réduite, voire inexistante et l'amorçage de fissure intervient alors tôt dans la durée de vie totale.

La phase finale se limite aux quelques derniers cycles : elle est accompagnée d'une forte déformation plastique du reste de la structure.

2.3 - DUREE DE VIE A L'AMORCAGE D'UNE FISSURE DE FATIGUE

Depuis longtemps, la philosophie adoptée par les constructeurs de moteurs, dans le domaine de la prévision de durée de vie des disques est fondée sur une approche de la fatigue oligocyclique qui s'appuie sur le concept de "Durée de vie à initiation d'une fissure". Ce concept considère que la durée de vie du disque est limitée par la présence d'une macro fissure dont la taille au sens de l'ingénieur est de quelques dixièmes de mm. Dans cette approche, le temps nécessaire pour que cette crique évolue jusqu'à une taille critique entrainant la rupture, n'est pas pris en compte dans la détermination de la durée de vie autorisée en service.

Une fois cette durée de vie atteinte les disques sont retirés de la circulation quelques soient leurs états. Toutefois, à cause des facteurs de sécurité considérés (dispersion des propriétés mécaniques en fatigue des matériaux, conditions de fonctionnement imprévisibles), l'emploi de cette philosophie peut se révéler très conservatif en regard de la durée de vie potentielle réelle des pièces. En effet, sauf cas particulier , la présence d'une fissure sur un disque entraîne son retrait du parc.

Au stade du dimensionnement, la durée de vie est prédite sur la base de quatre types d'informations |2| :

- une banque de données, regroupant les conditions d'utilisation du matériel (profil de mission, répartition statistique des températures, hypothèses de dégradation....),

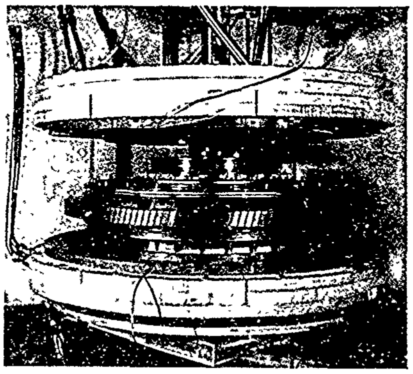
- une caractérisation très poussée des matériaux en laboratoire, corrélée aux gammes d'élaboration des bruts et de fabrication de la pièce finie,

- un ensemble de calculs plus ou moins sophistiqués, selon l'état d'avancement du projet reposant sur la méthode des éléments finis,

- un programme d'essais partiels sur maquettes en araldite figées sous charge et analysées par photoélasticimétrie tridimensionnelle.

C'est enfin en fosse de survitesse que sont reproduites les sollicitations thermiques et mécaniques : la durée de vie théorique est validée par ces essais (fig. 2).

L'analyse de disques rompus sur banc cyclique permet de mettre en évidence les effets de la fatigue oligocyclique, qu'il est intéressant de corréler avec l'observation de pièces rompues en service d'une part, et d'éprouvettes de laboratoire d'autre part. Dans certains cas, il est possible de faire quantitativement la liaison pièce - éprouvette, et de recalculer les divers stades de la durée de vie |3|.



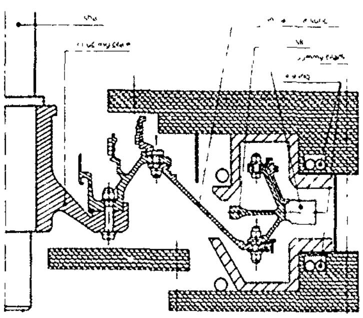


Figure 2 : Montage d'essais en fosse d'un disque

2.4 - DUREE DE VIE EN PROPAGATION D'UNE FISSURE DE FATIGUE

De nouvelles philosophies basées sur des concepts de "Tolérance au dommage" ou de "Durée de vie totale", sont maintenant envisagées en alternative.

Dans la "Tolérance au dommage", on suppose qu'il existe une fissure potentielle de taille égale au seuil de détection des moyens de contrôle non destructif employés. Le calcul s'appuie alors sur le temps pour que cette fissure atteigne une taille critique, celui-ci servant à définir un intervalle d'inspection lors de chaque inspection, si aucune crique n'est détectée, le disque peut être réutilisé pendant un nouvel intervalle de révision, le but final étant de ne déposer le disque, que si une crique est détectée.

Plus séduisante, l'approche par le concept de "Durée de vie totale" considère que la durée de vie du disque est constituée de toutes les étapes de l'endommagement menant à la rupture d'une structure, l'initiation puis la propagation d'une fissure. Synthèse des deux philosophies précédentes (voir figure 3), elle en allie les avantages et offre au concepteur la possibilité, pour une durée de vie objectif donné, de privilégier plus ou moins l'une des phases d'endommagement par rapport à l'autre en jouant sur le niveau des contraintes à atteindre, permettant ainsi de faire varier la masse des disques à étudier.

Néanmoins, des difficultés de deux ordres subsistent pour l'application concrète de ces méthodes :

- développement de modèles de calcul de pièces en fissuration,

- connaissance précise, au niveau du matériau, des différents stades de la fissuration que l'on peut physiquement décrire en trois étapes (fig. 4).

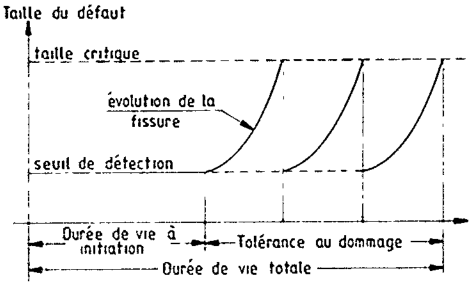


Figure 3 : Philosophies de dimensionnement

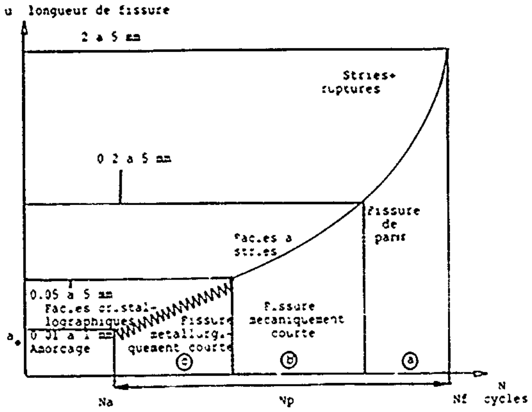


Figure 4 : Stades de la durée de vie en fissuration par fatigue

a) Stade où les modèles classiques (Paris, Forman...) s'appliquent : c'est le domaine de la mécanique linéaire de la rupture, régie par des relations entre da/dN (vitesse de propagation de fissure) et Δ K (facteur d'intensité de contrainte),

b) Stade où le principe de similitude de la mécanique de la rupture ne s'applique plus , c'est le domaine des fissures mécaniquement courtes décrit par un faisceau da/dN = f (Δ K, $\Delta\sigma$ ...),

c) Stade où la progression de fissure paraît gourvernée par la microstructure (fissures "métallurgiquement courtes"). C'est le domaine de la mécanique de l'endommagement.

Le deuxième stade (b) commence à être étudié systématiquement.

Le troisième stade (c) demeure encore dans le domaine de la recherche de base.

La solution de ces problèmes se trouve encore compliquée par :

- la présence de contraintes vibratoires, non simulables en fosse de survitesse, qui peuvent augmenter de plusieurs ordres de grandeur les vitesses de propagation.

- les effets de l'environnement, qui jouent un rôle important pour certains alliages.

La mise en oeuvre de ces concepts semble d'autant plus nécessaire qu'avec des disques fortement chargés en alliage à haute résistance, les tailles de défauts critiques sont faibles, et la majeure partie de la durée de vie de propagation est effectuée entre quelques dixièmes de mm et 1 mm environ. Il sera, dans ces conditions, nécessaire d'intégrer dans le dimensionnement de la pièce, cette partie de la durée de vie pour atteindre les objectifs de potentiel souhaités.

Compte tenu du travail qu'il reste encore à accomplir pour développer des modèles de propagation dans des milieux tridimensionnels, qui soient capables de représenter de façon satisfaisante les effets des variations de températures et de contraintes rencontrés en service, le dimensionnement de certaines structures de turbomachines à la fatigue oligocyclique reste pour l'instant essentiellement basé sur le concept de "Durée de vie à initiation".

2.5 - MODELES DE COMPORTEMENT DES MATERIAUX

Dans le domaine de la prévision de durée de vie à initiation, la SNECMA utilise pour le dimensionnement des structures fortement sollicitées des modèles de comportement unifiés (couplage des déformations plastiques et visqueuses) et de dommage continu développés par l'ONERA, en effet une bonne prévision de durée de vie ne pouvant être faite que si le champ de contraintes est connu avec précision dans la structure.

Le comportement du matériau est décrit à l'aide d'équations constitutives qui définis-

sent la relation qui existe entre les contraintes et les déformations en fonction du temps et de la température. Elles superposent les principaux phénomènes viscoplastiques rencontrés sur les matériaux (voir figure 5) soumis à des sollicitations cycliques. A savoir :

- l'écrouissage cinématique (non linéaire et/ou linéaire) qui définit l'évolution dans l'espace des contraintes, du centre du domaine élastique,
- l'écrouissage isotrope qui traduit les variations cycliques du rayon élastique,
- la contrainte visqueuse qui provoque l'écoulement viscoplastique,
- les effets de restauration induits par la température qui diminuent lors des temps de maintien les effets de l'écrouissage.

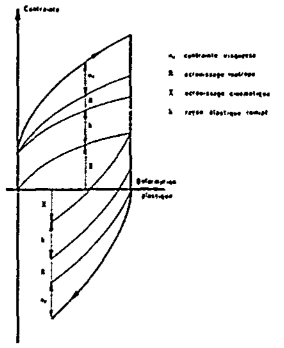


Figure 5 : Phénomènes viscoplastiques

Ces modèles conduisent à des lois où interviennent des coefficients caractéristiques des matériaux fortement dépendants de la température. Leur nombre est fonction de la complexité du comportement que l'on désire traduire. Ces coefficients sont identifiés à partir d'essais uniaxiaux isothermes appropriés (traction monotone, essais cycliques, de fluage ou de relaxation).

La SNECMA utilise une description du comportement viscoplastique du matériau basé sur les modèles unifiés proposés par Monsieur CHABOCHE |1|, ces modèles très complets décrivant une large gamme de phénomènes pouvant prendre la forme suivante :

$$\dot{P} = \left\langle \frac{J(\sigma' - X') - R - r}{K} \right\rangle^{n} \times \operatorname{sign}(\sigma - X)$$

l'écrouissage cinématique s'écrivant sous la forme

$$\dot{X} = C\,(a\,\dot{\varepsilon}p - X\,|\dot{\varepsilon}p|) \quad \text{et}$$

$$\dot{R} = b\,(Q - R)\,\dot{p}$$

avec R, n, k, r, c, a, Q, b, coefficients du modèle

2.6 - MODELE D'ENDOMMAGEMENT CONTINU

Reprenant le concept de la contrainte effective proposée par KACHANOV pour définir l'évolution du dommage en fluage pur, ces modèles s'appuient sur deux lois de dommage |1|. L'une, de fluage pur, exprime l'accroissement de dommage provoqué par les contraintes au cours d'une variation de temps. L'autre, de fatigue, s'appuie sur des paramètres de contraintes représentatifs de la sollicitation cyclique (contraintes moyennes et maximum du cycle, amplitude de variation des contraintes), pour exprimer l'augmentation de dommage obtenue au cours d'un cycle. Les effets du couplage, entre les endommagements de fluage et de fatigue sont pris en compte par l'intermédiaire d'une sommation des accroissements de dommage calculés au cours d'un cycle par chacune des lois.

Ces deux lois peuvent être écrites sous la forme suivante :

$$dD = dDf + dDc \quad \text{avec}$$

$$dDc = \left[\frac{\chi(D)}{A}\right]^{r} (1 - D)^{-K(\sigma)}$$

$$dDf = \left[1 - (1-D)^{\beta+1}\right]^{\alpha(\alpha m-\bar{\alpha} M)} \left[\frac{A_{II}}{M(\bar{\sigma})(1-D)}\right]^{\beta} dN$$

avec A, r, K, β coefficients du modèle et α, M fonctions.
et $\chi(D)$ la fonction de HAYURST.

Comme pour les modèles de comportement, les coefficients caractéristiques des matériaux qui apparaissent dans ces lois de dommage sont également dépendants de la température et leur identification s'appuie sur des résultats en fatigue et fluage d'essais à rupture uni-axiaux isothermes.

2.7 - MODELES DE PROPAGATION DE FISSURES

Dans le domaine de la prévision de la durée de vie résiduelle des structures la SNECMA utilise depuis plusieurs années pour le calcul de la propagation des fissures, des modèles basés sur la mécanique linéaire de la Rupture. Le facteur d'intensité de contrainte d'une fissure semi-elliptique contenue dans un barreau infini est obtenu par :

- la formulation développée par IRWIN avec des facteurs de correction pour tenir compte des caractéristiques géométriques exactes (F1, F2, F3 F4) :

$$K_I = \sigma . F1 . F2 . F3 . F4 . \sqrt{\pi a / \phi}$$

- la formulation proposee par NEWMAN et RAJU avec des facteurs de correction :

$$K_I = \left[\sigma_T + H \sigma_B\right] \sqrt{\pi a} \quad F\left(\frac{c}{a}, \frac{a}{t}, \frac{c}{\ell}\right)$$

- éléments finis tridimensionnels (voir figure 6) permettant d'obtenir le facteur d'intensité de contrainte par la méthode des déplacements en pointe de fissure :

$$K_I = \frac{E}{4(1-\nu^2)} \sqrt{\frac{2\pi}{\ell}} (4Vi - Vj)$$

ou par la méthode du taux de restitution d'énergie ("Virtual crack extension").

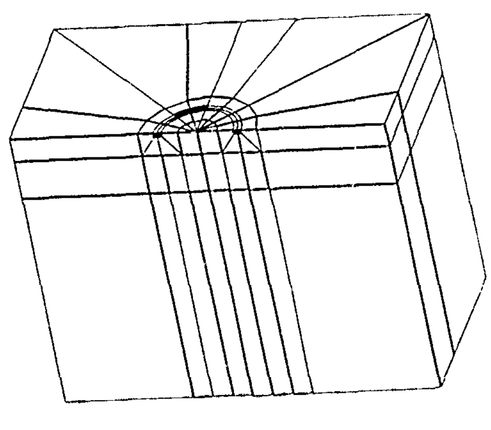


Figure 6 : Modèle éléments finis d'une fissure dans une éprouvette

La propagation de la fissure sous un chargement complexe ne peut être analysée par un cumul linéaire cycle par cycle ; elle est obtenue par un modèle basé sur la notion de facteur d'intensité de contrainte effectif, développé par ELBER et modifié par l'ONERA |4| où le K ouverture est remplacé par un K seuil dépendant des histoires du chargement et du K seuil.

La figure 7 montre les résultats de ce modèle |5| pour une séquence d'essais TURBISTAN.

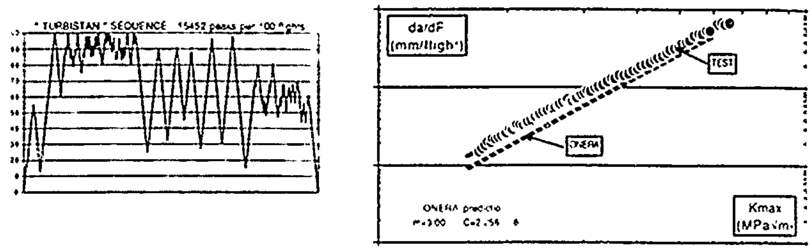


Figure 7 : Essais sur INCO718 à 450° C sur séquence TURBISTAN

3 - APPLICATION DES MODELES AU DIMENSIONNEMENT A INITIATION

3.1. CALCUL DE STRUCTURES PAR ELEMENTS FINIS

Utilisés depuis plusieurs années déjà sous leur formulation uniaxiale pour le dimensionnement des aubes fixes ou mobiles de turbine |6|, leur passage à une formulation multiaxiale a permis une extension de leur utilisation au dimensionnement d'autres types de structures.

Aujourd'hui, leur implantation dans le code éléments finis SAMCEF |7| employé par les bureaux d'études de la SNECMA, étend leur domaine d'application aux principales structures des turbomachines.

La mise en oeuvre des procédures de dimensionnement utilisées conduit à la réalisation successive des étapes suivantes :

- définition de l'évolution temporelle des températures et chargements mécaniques représentatifs des conditions de fonctionnement des composants étudiés,
- choix des équations constitutives décrivant le comportement du matériau utilisé. Aux températures élevées, des lois viscoplastiques sont nécessaires,
- calcul de l'évolution des contraintes et déformations dans la structure à l'aide d'une modélisation éléments finis, jusqu'à obtenir une réponse cyclique stabilisée,
- application des lois de cumul de dommage afin de déterminer le nombre de cycles à initiation, à partir des résultats en contraintes obtenues à la réponse cyclique stabilisée.

Une des principales difficultés de la mise en oeuvre de cette procédure de prévision tient à la complexité des effets à représenter. Compte tenu de la non linéarité des phénomènes, la recherche de l'évolution temporelle du comportement de la structure jusqu'au cycle stabilisé nécessite des moyens de calcul informatiques notablement plus importants que pour les analyses éléments finis élastiques ou élastoplastiques traditionnelles.

En effet, compte tenu des phénomènes de redistribution des contraintes dans les zones plastifiées (voir figure 7) et des variations de comportement du matériau induits par les sollicitations cycliques (relaxation de la contrainte moyenne, adoucissement ou durcissement cyclique), l'obtention de la réponse stabilisée peut conduire au calcul d'un nombre de cycles (vols) consécutifs plus ou moins importants.

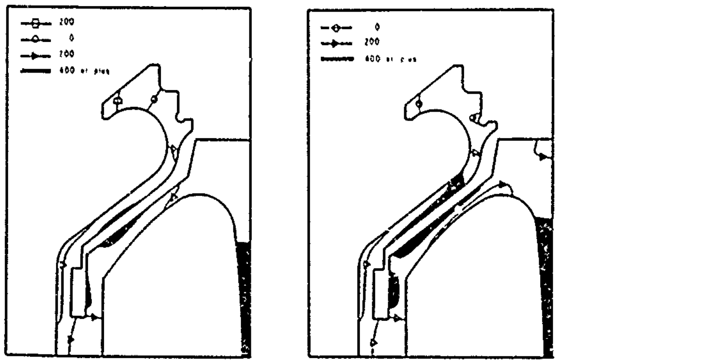


Figure 7 : Redistribution des contraintes circonférentielles sur un rotor de turbine suite à un temps de maintien à haute température

3.2 - ANALYSE D'UNE AUBE DE TURBINE

Un autre exemple présenté dans cet exposé de l'utilisation des modèles de durée de vie à initiation concerne l'aube de turbine refroidie du corps HP du moteur LARZAC. Cette aube est en superalliage IN100 avec un système de refroidissement sophistiqué

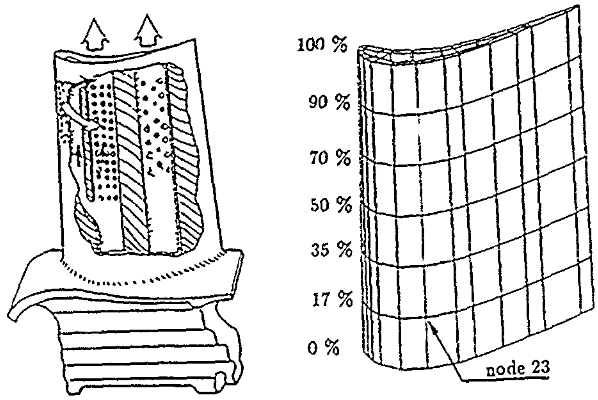


Figure 8 : Géométrie et maillage de la pale

La figure 9 présente le chargement mécanique et thermique transitoire de la pale dans des conditions d'essais partiels.

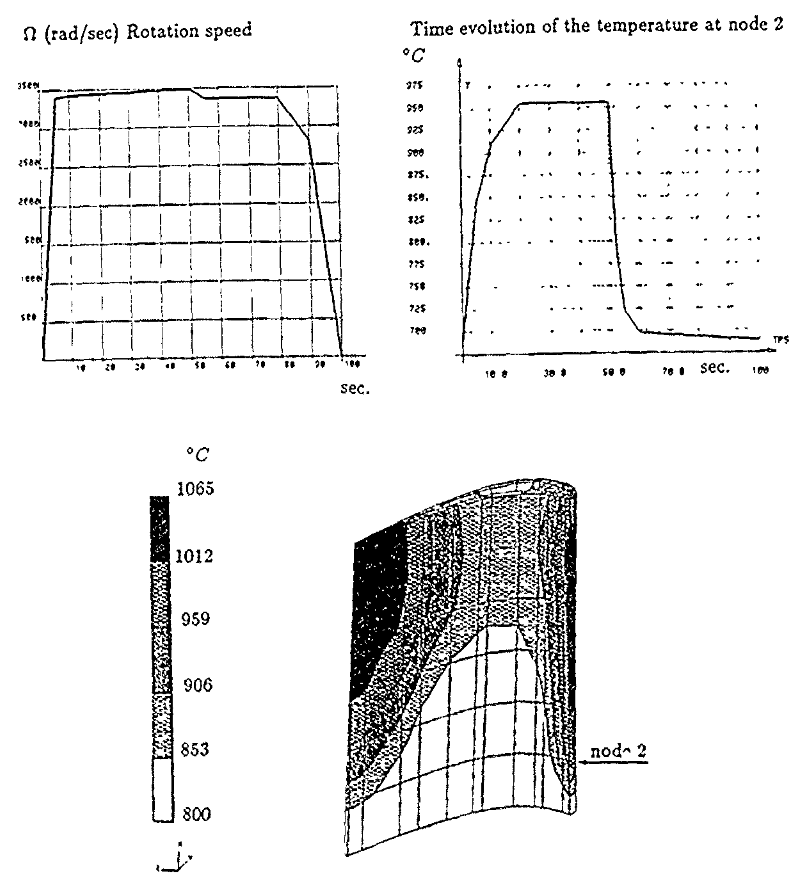
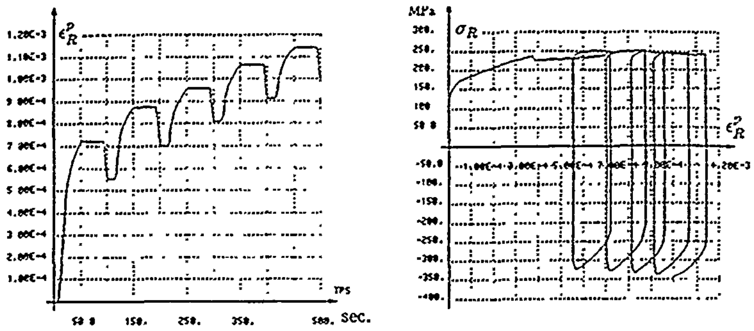


Figure 9: Cycle de chargement thermique et mécanique de l'aube

Le calcul par éléments finis a été réalisé en modélisant le comportement du matériau à l'aide d'une loi viscoplastique à cinq paramètres avec écrouissage cinématique non linéaire décrivant parfaitement le cycle stabilisé du matériau.

La figı e 10 montre la distribution de déformation plastique cumulée au cours du cyclage et au cycle stabilisé. Les éléments ayant la plus grande déformation plastique sont localisés au bord de fuite à mi-hauteur de l'aube. La zone critique et la durée de vie calculée par les modèles de dommage continu correspondent bien aux constatations expérimentales .



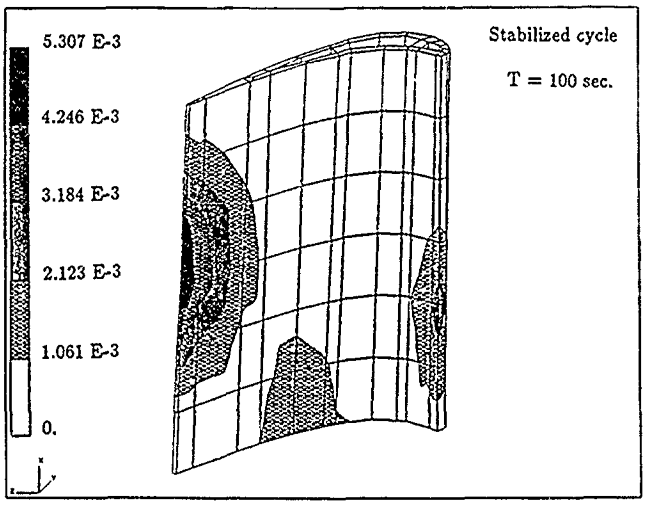


Figure 10 : Déformation plastique cumulée à la fin du cycle stabilisé

4 - APPLICATION DE LA TOLERANCE AU DOMMAGE

L'application de la Tolérance au Dommage demande à bien connaître les données suivantes :

- histoire précise des conditions de fonctionnement
- caractéristiques de propagation de fissure sous les conditions de sollicitation appropriées (rapport de charge, temps de maintien,...)
- précision et confiance des moyens de contrôle non destructifs pour la détection des défauts.

Le dernier point est très important puisque c'est lui qui pratiquement détermine la durée de vie résiduelle de la structure, donc la durée de l'intervalle entre inspections qui peut être fixé pour les composants critiques du moteur.

Comme le montre la figure 11 sur les alliages classiques sans défaut initial, il existe un écart important entre la durée de vie à initiation ("safe life") associée à une proba-

bilité de 1/1000 et la durée de vie en propagation à partir du seuil de détection.

Cet écart peut être réduit par un développement des moyens de contrôle non destructif et par une amélioration des caractéristiques en fissuration du matériau, mais sur certains composants cela se fera sans doute au détriment de la masse.

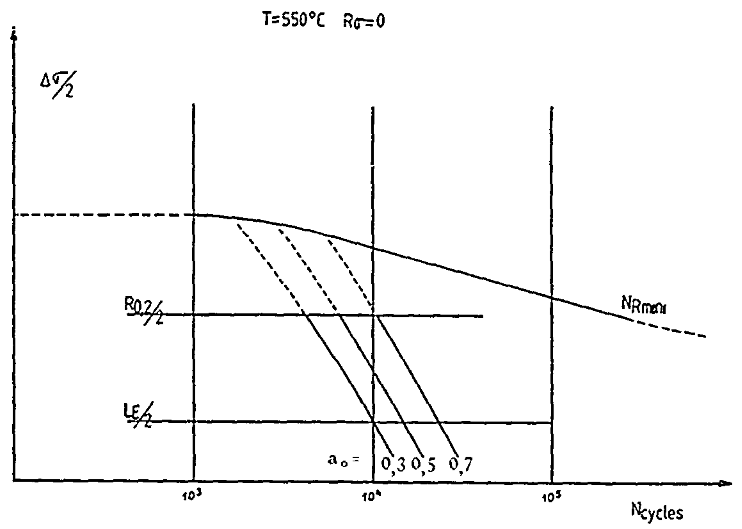


Figure 11 : Comparaison durée de vie à initiation et en fissuration

Le calcul de l'évolution des contraintes et déformations dans la structure à l'aide de modélisations éléments finis pour obtenir la réponse cyclique stabilisée du matériau, se fait suivant les mêmes principes développés au paragraphe 2.5.

La figure 12 présente un exemple d'étude tridimensionnelle de la durée de vie résiduelle d'un disque de compresseur HP. Cette analyse est faite en supposant que la fissure garde un même type de forme et que son avancée est pilotée par le facteur d'intensité de contrainte obtenu à partir de plusieurs fronts de fissure obtenus à partir d'un même maillage Cette étude a été menée avec technique du super élément pour en optimiser le coût et la durée.

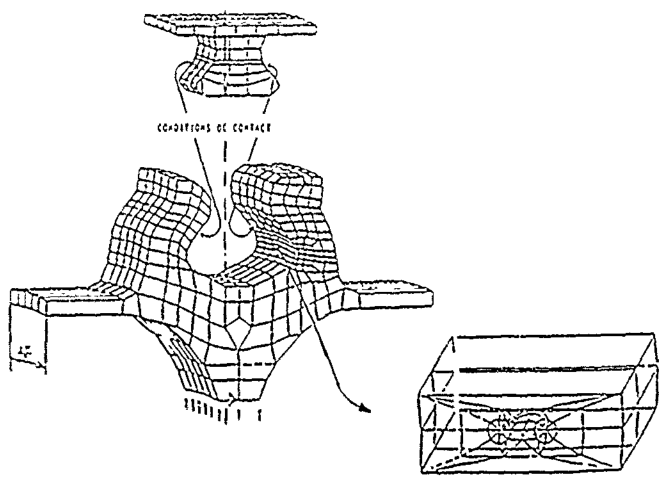


Figure 12 : Exemple d'étude en fissuration d'un fond d'alvéole de disque de compresseur avec le détail des éléments variables contenant la fissure

4 - CONCLUSION

Aujourd'hui, la conception de turbomachines à hautes performances, nécessite de disposer de méthodes de dimensionnement à la fatigue oligocyclique à chaud, capables de représenter le plus correctement possible, les évolutions du comportement jusqu'à la rupture des composants moteur les plus sollicités.

Compte tenu des niveaux de contraintes atteints et des températures rencontrées en service, le niveau de confiance demandé aux prévisions de durée de vie est tel que les approches traditionnelles doivent être remplacées par des approches permettant de prendre en compte mes effets non-linéaires de comportement et d'endommagement observés sur les matériaux utilisés.

Dans le domaine de la prévision de durée de vie à initiation, la SNECMA utilise des méthodes basées sur des modèles de comportement viscoplastiques et d'endommagement continu développés par l'ONERA. Employés depuis plusieurs années déjà pour le dimensionnement des aubes de turbine, l'usage de ces méthodes, suite à leur implantation dans le code éléments finis SAMCEF utilisé par la SNECMA, s'est étendu au dimensionnement des principales structures des turbomachines étudiées.

Bien que le dimensionnement des structures en fatigue oligocyclique reste pour l'instant essentiellement basé sur des calculs de prévision de durée de vie à initiation d'une fissure, les calculs de prévision de durée de vie en propagation des fissures sont appelés à jouer un rôle croissant. Toutefois, compte tenu des phénomènes à représenter, les modèles de propagation proposés aujourd'hui, qu'ils soient basés sur une approche par la mécanique de la rupture ou sur une approche locale de la progression de la fissure nécessitent encore de très importants développements pour permettre au concept de Tolérance au Dommage de se substituer au concept de "safe life", principalement pour des applications civiles.

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THE ROLE OF COMPONENT TESTING

by

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SUMMARY

Component testing performs a major role in design and life management and by virtue of

- representation of engine conditions
- incorporation of all the significant variables
- the testing of a significant volume of material and number of repeated features

is one of the most powerful tools available in ensuring that design and life goals are met.

Component testing is integrated with laboratory investigation and material data generation to provide a material data bank that can reliably be used for design and service life prediction. Modern techniques of stress and fracture mechanics analysis, crack monitoring and metallography and probabilistic approaches are employed. The understanding of material behaviour in component form that is built up following this approach, in which component testing can be used in a diagnostic or research role, leads to the development of new and improved materials.

The above are discussed under the headings of:

- o Types of test.
- o Relationship of test conditions to engine cycles.
- o Testing. facilities
- o Test monitoring techniques.
- o Test analysis
- o Scatter effects.
- o Use of results in component behaviour analysis.
- o Future use of component testing.

INTRODUCTION

Context

The role of component testing is best seen in the context of an integrated procedure for design, service life estimation and service life management.

Such a procedure has the objective of satisfying the Customer requirement for an engine with high performance, low weight, high integrity and life and low parts and maintenance costs.

An example of this type of procedure is shown, in flowchart form, in Figure 1 and incorporates the following activities

- performance
- temperature estimation
- stress analysis and mechanical design
- materials behaviour
- life estimation
- validation tests and measurements
- product assurance
- life management procedures

Validation role

The fundamental role of component testing is to validate service life predictions, by testing components made to the correct specifications under conditions as nearly representative of the engine as possible.

This validation is required because of

a) uncertainties in stress-strain predictions from finite element models due to

- complex geometry
- complex loading at interfaces
- constitutive relationships for cyclic stress and strain in the material in nonlinear complex fields based on uniaxial test results

b) uncertainties in the prediction of fatigue behaviour on the basis of laboratory specimens alone due to

- unrepresentatative surface machining and processing
- inadequate representation of the component stress field and stress-strain cycle by the specimen tests
- omission of residual stresses
- omission of interface compressive and frictional effects
- inadequate volume of material tested to cover the probability of either surface or subsurface flaws being present in the component

Attributes

Cyclic testing of components made to the engine specification (sometimes test-pieces cut from engine components) has the following major attributes.

a) The material is tested in the form that is most representative of the service component, in terms of material manufacture and surface machining and processing.

b) The induced stresses and strains are as representative of those in the engine as possible. Testing incorporates

- residual body stresses from forging and quenching
- residual surface stresses from machining and processing
- localised stress distributions at individual blade attachments and similar features
- the influence of bi- and tri-axiality on stress and strain redistribution due to yielding and creep.

c) External loading effects are reproduced. This is particularly important at interfaces such as blade-disc attachments, where the combined effects on fatigue life of compressive and frictional stresses and fretting can be significant.

Data, Understanding

By the generation of significant numbers of component test results and interpreting them using laboratory and stress analysis techniques a better understanding of material behaviour in component form can be obtained and it becomes possible to calibrate laboratory specimen test results against those from components.

Material data banks can then be built up from which service LCF lives can reliably be predicted at the design stage.

Analytical methods

Reliable prediction of service life rests as much on the correct analytical prediction of cylic stresses, strains and temperatures as it does on the availability of valid fatigue data.

Hence optimised design requires validated analytical and modelling techniques as well as validated material properties (not limited to fatigue data).

This can be assisted by strain-gauging and growth measurement of tested components to validate the elastic and plastic finite element programs that are used as design tools.

Life management

When continued into the steady crack propagation phase, component testing results can be used in the life management procedure for prediction of safe inspection increments, either on the basis of damage tolerance or retirement for cause.

The initial discontinuity sizes that can be present in a new component at entry into service, particularly those resulting from surface machining, processing and handling damage, can be significantly smaller than those that can be detected by Non-Destructive Inspection. The characterisation of these initial discontinuities and the use of probabilistic analysis subsequent to component testing can result in higher initial lives being released at entry into service than are permissible when damage tolerance lives are based on NDI capability.

Evaluating changes

Component testing can be used as a means of evaluating changes in material fatigue properties subsequent to service exposure, eg corrosion, but, due to the obscuring effect of scatter, is not normally effective as a means of monitoring service life usage.

Material development

There is a role during the development of a new material for testing in component form, to ensure that the required properties can be met in a forging of representative size. Emphasis here is generally on bulk behaviour.

TYPES OF TEST

Objectives

Tests on components are carried out with the following objectives:

a) to validate the predicted behaviour of the components in service

b) to calibrate material data obtained from laboratory test results

c) to validate and develop methods of calculation and modelling

d) to diagnose problems and unanticipated behaviour

e) to improve the understanding of material behaviour in component form

f) to lead to new material developments

The tests may be carried out in a variety of ways to measure stress, strain, growth, life, crack size and failure conditions.

Generic types

The generic types of test carried out are as follows.

o Proof and Ultimate - in the Damage Tolerance context these are:

a) to demonstrate that the size of any crack in the component is low enough to permit the part to (re-)enter service for a specified life related to the crack size (eg. cryogenic test).

b) to confirm the capability of the component to meet design requirements with the maximum size of crack that can be present in service.

o Low Cycle Fatigue - this is the most common concerning Damage Tolerance

o High Cycle Fatigue

o LCF/HCF combined

o Creep/Dwell - at steady conditions where time effects dominate

o LCF/Creep/Dwell - at cyclic conditions simulating time on/off load in the engine cycle

o Residual Stress - to measure residual forging, heat treatment and machining stresses

o Measurement of temperature, displacement, strain, growth, crack growth

- used for methods and modelling validation purposes, on tests set up specifically for this purpose or to enhance the data provided by other tests.

Reproducing engine conditions

The fundamental principle for all testing is that the test conditions either reproduce, or can be related to, those on the engine.

For example, suppose that the final machining of a disc results in tensile residual stresses and damage to the surface microstructure and that it is therefore followed by vapour blasting to remove some of the surface layer and then by shot peening to introduce compressive stresses. To quantify the life capability via testing there are then two options:

a) carry out fatigue tests on the finally processed surfaces

b) measure the residual stresses and quantify the microstructural damage at each stage of manufacture in order to calculate their combined effects analytically from basic material data.

When such effects are not easily quantifiable, particularly when there are several variables and the contribution from each is uncertain, there is a great deal of merit in testing the full-size component in the way that reproduces engine conditions. This can be followed by research when a more detailed understanding of the individual effects is required. An advantage of this approach is that it gives the whole picture first, indicating what is significant and worth research effort. Carrying out research to establish the individual effects of all potential factors that could influence fatigue behaviour is less likely to be as efficient.

RELATIONSHIP OF TEST CONDITIONS TO ENGINE CYCLE

Engine cycle

The first major step is in the accurate prediction of the engine cycle of

- stress
- strain
- temperature

at each critical feature of the component throughout each type of sortie of the aircraft.

The extent of this work in total can be seen by reference to figure 1. It is the block comprised of

- performance
- air system temperature
- metal temperature
- stress and strain
- vibration

analysis and validation.

Analysis

In today's environment the stress/strain/temperature cycle at each critical feature eg.

- bore
- drive
- fillet radius
- diaphragm (web)
- hole
- rim
- blade attachment
- weld

is calculated using advanced finite element techniques, allowing where necessary for geometrical, plastic and creep nonlinear effects.

However there can still be uncertainties in the modelling of complex features, particularly at contact faces where there is sliding and friction, and at conditions of material nonlinearity where constitutive relationships for triaxial behaviour are based on uniaxial material test data.

Cross reference

The component is modelled and analysed for the test in the same way and with the same degree of refinement as for the engine. This provides a cross-reference between test and engine conditions even if there are complex features that are difficult to model. Ensuring that the cross-reference chosen is valid, ie that the rig and engine both impose the same conditions, even though the behaviour may be complex,is an essential part of test preparation. Examples are given in the text under "Testing Facilities" of the way conditions are reproduced in practice.

Representative result

Having achieved satisfactory reproduction of engine conditions, each test result can be treated as a statistical sample of component behaviour as it will be on the engine. If this turns out to be different from the behaviour anticipated from laboratory testing, this difference can be pursued by diagnostics or on a research basis until it is understood.

Service life

Once the relationship between the engine cycle and rig test conditions has been established, two routes can be followed (fig. 12) in order to validate the safe service life (in total or as inspection intervals).

a) direct relationship of the service life to the component test results.

b) the use of component test results to calibrate and underwrite a material data bank from which service lives are predicted.

The minimum service life capability is then derived from statistically based scatter factors, according to the number of test results available:

- a small number, following the "direct" route
- a larger number, supporting the "data bank".

Both methods are based on the concept that engine stress and temperature conditions can be reproduced in a component test with sufficient accuracy that the test life provides one sample of service life capability.

TESTING FACILITIES

Objective

Component testing is directed towards reproduction of engine conditions.

The type of facility selected to test a component therefore depends on

a) its capability to simulate the engine conditions

b) economics and availability.

Generic facilities

The generic testing facilities needed are

- load rods and jacks
- air and oil pressure supply
- heaters
- servohydraulics
- spinning rigs
- optionally, Ferris Wheel rigs (axisymmetric array of radial load rods and jacks)
- with control, instrumentation and recording systems.

In the construction of test plant and its environment there are stringent requirements regarding health and safety, in particular noise and protection from high energy debris when components are tested to failure.

Inspection and Laboratory investigation facilities are essential in order to interpret and quantify behavioural aspects.

In the following paragraphs the capabilities of various types of rigs to reproduce engine conditions, and some of the practical considerations, will be discussed.

SPINNING RIGS

The facility most commonly used by Rolls-Royce for testing critical rotating components is the cyclic spinning rig (fig.2).

The rotating assembly is driven by an electric motor, via a gear box. To reduce power losses the test compartment is partially evacuated, also "dummy" blades without aerofoils are often used. To reduce damage to the gearbox after bursting of a test rotor, a flexible interconnecting shaft is incorporated; this introduces a requirement for accurate balancing.

Heating is supplied by radiant heaters mounted from frames in the test compartment. In general the objective is to test at constant temperature through the cycle. When steady temperature gradients are required these are obtained by adjusting heaters, shielding and introducing cooling coils. Cyclic heating and cooling is not practical, the heating and cooling rates achievable are very much slower than in an engine.

Temperatures are controlled by thermocouples within the test compartment. Metal temperatures are confirmed at intervals by taking readings from proximity probes. Additional instrumentation in the form of straingauges and thermocouples attached to particular features of the rotor is introduced when necessary.

Rotor speeds and temperatures are continuously monitored and trips are included in the control system to prevent accidental overspeed and to shut the rig down subsequent to burst or excessive vibration. It is common practice to cycle from (near)zero to maximum RPM but if necessary a more representative cycle can be introduced.

The test assembly is surrounded by blocks of soft material, in order to minimise damage to fracture faces in the event of a rotor burst, to allow a full laboratory investigation of the origin, form and rate of crack growth. The layer of soft material is surrounded by the steel vacuum tank and a layer of concrete for safety. Special precautions are taken to reduce the rig noise to an acceptable level.

Attributes

The main attributes of testing full size components on a spinning rig are as follows.

a) The material is tested in the form that is most representative of the service component, in terms of material manufacture, surface machining and processing.

b) The volume of material and numbers of features tested are significant.

c) Induced stresses and strains are as representative of the engine as possible.

Testing incorporates:

- residual body stresses from forging and quenching
- residual surface stresses from surface machining and processing
- localised stress distributions at individual blade attachments and similar features (point radial loads from blades do not immediately diffuse into the disc as assumed in axisymmetric models)
- the influence of bi- and tri-axiality on stress and strain redistribution due to yielding and creep.

d) The interface load effects between blades and discs are reproduced. This is particularly important due to

- local compressive and frictional effects
- the effects of wedge angle and skew in an "axial" blade slot.

Engine stress distributions can only satisfactorily be reproduced on rigs that apply the radial blades loads round the complete circumference of the rotor, viz. spinning rigs and Ferris wheels.

e) The length of a fatigue crack prior to fracture is generally much longer in a full size disc than a laboratory specimen. The direction that the crack will take in the engine (which may be uncertain on the basis of calculation alone, especially in root slots) can therefore be predicted with some confidence from the rig test and the safe life margin confirmed.

Reproduction of engine conditions

Difficulty in reproducing engine conditions normally only occurs when there are significant stresses due to transient thermal gradients through the component. Axial gas forces on the blades and pressure differences across the faces of a disc do not usually cause significant problems but care has to be taken when blade and disc mass distributions have been adjusted in the design to compensate for gas/pressure bending moments in the engine, which will be different for the vacuum rig.

Cold parts

In the simplest case, a component such as a fan disc, at the cold end of the engine, with a minimal thermal stress gradient, can be tested to give results via the "direct" route, simply by relating test to engine RPM without any stress analysis.

In this case the test can cover all features on the component.

This formed the original basis for cyclic spinning testing of discs, in the 1950s, when only "body" stresses could be estimated, and these often with reservations on accuracy if there were redundant or complex features.

Modest temperature gradients

The forward compressor and the rearmost turbine stages generally have only modest temperature gradients and it is usually possible to simulate a number of features on the same rig test. The practice of reproducing maximum stresses due to temperature gradients by increases in RPM is common. The bore of a disc has generally been regarded as a critical zone, being at the highest surface "body" (as opposed to local concentrated) stress due to the combination of centrifugal and hot rim/cold bore stresses during the take-off transient. (The bore hoop stress tends to be at its highest at take-off and the rim hoop stress at its highest at stabilised conditions).

Standard practice is to set the stress/temperature conditions at the most critical location, eg. (fig.3) one of:

- bore
- drive
- fillet radius
- diaphragm (web)
- holes
- rim
- blade root attachments
- welds

at or slightly above those of the engine, with the adjacent stress gradient as representative as possible. The applied "stress scatter factors" can be converted to "life scatter" factors using S-N curve slopes; this may result in a different potential life being cleared for each feature, the lowest one dictating the service life.

Setting the RPM higher to reproduce the maximum bore surface stress can result in the other features, such as rim concentrations, in being overtested. Some compensation for this can be introduced by using dummy blades that are lighter than those on the engine, but if this is not possible normal practice is to machine the overstressed feature off in order to obtain a definitive result for the bore (or similarly for any other feature tested).

High transient temperatures

The most difficult problems are in the rear High Pressure compressor and in the HP turbine (fig.4) stages.

a) Transient cooling from the gas stream during pull-back (decel.) can cause high rim hoop and compressive radial diaphragm (web) stresses.

   This effect can be simulated by a steady temperature gradient induced by radiant heaters and cooling coils.

b) Transient gradients due to heating-up of the surfaces during take-off (and to a lesser extent during other accelerations) can result in significant tensile body stresses in the middle of the disc cob (fig.5).

This causes the greatest difficulty in simulation, as a disc in a vacuum rig cannot be heated up and cooled down at the same rate as in an engine. Residual stresses in the bore do tend to protect it and thus allow the cob to be cycled at a higher stress than otherwise, but the correct engine distribution cannot be reproduced.

Component test results are however available for discs with subsurface embedded discontinuities in the cob region and these can be utilised in making safe service life estimates using fracture mechanics (fig.5).

AXIAL LOAD TESTS

Rotating rigs have been designed in which axial loads can be applied hydraulically in phase with the RPM. Test conditions are not easy to set up however and their use has been limited to cases of absolute necessity.

Static axial load tests on discs have been used with some success to represent local bending stress distributions in diaphragm (web) fillet radii features. The correct distributions are obtained by selecting the radii of the annuli to which the axial loads have to be applied, via Finite Element program trials and if necessary reprofiling one face of the disc.

FERRIS WHEEL TESTS

These rigs have the same capability as spinning rigs for testing rim features such as dovetail slots.

They have a number of advantages over a spinning rig for this application:

a) Test cycling of the hydraulic loading jacks can be faster than speeding up and slowing down a rotating assembly.

b) There is easier access for in situ inspection.

c) Environmental problems due to high rotating energy and noise are reduced.

Disadvantages are:

a) Dummy blades and load rod connections are more difficult to design than for the rotating rigs and engine blades cannot be used directly.

b) Bore and diaphragm stresses cannot usually be reproduced, the blade attachments cannot usually transmit as big a radial load as the body of a disc with centrifugal loading, also reprofiling may be necessary to get the right hoop-radial stress ratio in the rim.

c) Control systems may be needed to ensure that jack loads are in phase.

d) Insulation of hydraulic loading jacks is necessary for high temperature tests.

Certain Companies have generated a significant amount of valuable data using Ferris wheel installations, though Rolls-Royce discontinued the use of this type of rig in favour of spinning facilities, with their more general application.

UNIAXIAL LOAD TESTS

Uniaxial load tests on features cut from discs form an alternative to cyclic testing complete discs when the stress in one direction dominates, for example radial stresses in a circumferentially slotted compressor disc rim during a take-off transient (fig.6). Care has to be taken to avoid unrepresentative failures, eg. from edges.

This form of testing has the advantage that a range of stress levels and temperatures can be covered. By testing all the segments cut from a disc a significant volume of material is exposed and the increased information from testing at different stress and temperature levels may outweigh the loss in volume from material cut away during test-piece manufacture.

TESTS ON LOCAL FEATURES

In principle, if:

a) the volume of highly stressed material in a local feature is small

b) the engine stress-strain cycle can be simulated in a test using a static facility

c) cutting the test-piece from the disc does not remove significant conditions eg. residual stress

then, it may well be cost-effective to test a significant number of features cut from a disc separately, at different conditions, rather than together on the same rotating assembly and to analyse the results using some form of "extreme value" statistical method. Cycling an axial load rig/machine is usually faster than a spinning rig and inspection easier. Design of special end-fittings and cutting up and machining the test-pieces are the main delaying items.

This type of testing has been of particular use in comparing different surface machining/finishing methods. Complete discs are manufactured using production tooling and surface treatment applied by both research and production methods.

Adaptations of the "Compact Tension" type of specimen can be used to simulate stress gradients at particular stress concentration features, such as rim slots, or to investigate the effect of varying stress gradient.

TEST MONITORING TECHNIQUES

Test monitoring is carried out with these objectives in mind:-

a) Making sure that the intended conditions are imposed throughout the duration of the test.

b) Observing changes and, unless it is a test requirement, trying to stop the test before complete rupture occurs.

c) Making sure that the test provides as much data as possible for later analysis.

These general activities tend to overlap.

A non-trivial task is the preparing and publication of the test schedule and instructions, so that everyone involved knows what is being done, what to build, what has to be monitored and inspected, and when, and under what circumstances to shut down immediately.

The above objectives are achieved by

a) Test facility control, monitoring and recording systems.

b) Safety devices and precautions.

c) In-situ and tear-down inspections at specified intervals.

As much use as possible is made of continuous monitoring and in-situ inspection, to save build and strip times and costs but practically all fatigue testing requires regular inspections for cracks using laboratory facilities.

TEST FACILITY CONTROL, MONITORING AND RECORDING SYSTEMS

This is a subject in its own right.

Briefly, all loading systems and environmental conditions and observations must be controlled, monitored and recorded, whatever they are:- rotating speeds, torques, loads, pressures, temperatures. Monitoring systems generally have the dual applications of test control and safety precautions.

Measurements that can be taken to record change are much more easily made on a static than a spinning facility. Transducer measurements of displacement, straingauge and thermocouple monitoring, even Potential Difference recording to observe crack growth are all feasible under stationary conditions. Visual observation is also valuable on an open rig.

On a rotating rig (sealed, partially evacuated) roughness measurement often gives the first warning of incipient failure. Continuous monitoring by acoustic emission recording is being developed. Fatigue failures are not necessarily preceded by large bodily growth of the rotating assembly so that capacitance probes and contact trips, though used, have limited capability. Straingauge and thermocouple circuitry has tended in the past to require holes and slots to be cut in the rotating assembly and has been discouraged as not being conducive to the production of the intended fatigue test results.

Holography can be used as a diagnostic tool if a rig meets unforeseen vibration problems.

INSPECTION

Cracks

The detection of fatigue origins and cracks and the observation of rates of crack growth and critical sizes are of supreme importances in fatigue testing. These data are required for direct application in fatigue life estimation but are also needed for understanding of the material behaviour and failure mechanism.

The ideal way to carry out testing is to grow the fatigue crack to nearly a critical size and then cut it open, to avoid damage to the surfaces by impact after fracture. Common practice is therefore to inspect the component at regular intervals selected on the basis of crack propagation life to failure, starting on the basis of nucleation size, then on the basis of observed size.

Techniques

The primary problem is that only surface cracks are readily detectable (at a small size) using existing techniques - penetrant, binocular and eddy current inspections and crack closure due to residual stress can be misleading (though eddy current techniques can give warning before a crack is seen to break the surface). Subsurface cracks tend to grow perpendicular to hoop or radial stresses ie. in directions to which ultrasonics are insensitive. There is a requirement for development of better techniques - one problem has however been that as sensitivity is increased, so are the numbers of false signals eg. due to variation in grain size and structure.

Given the detection of a surface crack, its growth in observed length can be monitored, one method is by using replica techniques.

The information required however is the depth and shape of a crack as it grows. The only continuous recording method available is the Potential Difference method, which is only applicable currently via static tests, preferably in a laboratory environment and this method records area, the profile of the growing crack has to be deduced afterwards though this is not normally a problem (ref.2).

Currently therefore the rate of crack growth and the profile of the growing crack cannot be confirmed until after the test, when the component or test-piece is cut up in the laboratory for investigation.

Enhancement

Two techniques can be used to enhance the crack propagation information from a test, though these are not universally applicable. These are "heat tinting" and "beach marking".

Heat tinting, ie. production of discolouration by oxidising the surfaces of a crack by heating at a particular temperature, can be used to define the shape of a crack at some stage of the test, so that by continuing the test at another (cooler) temperature the colour of the extended crack is different.

Beach marking can be obtained by introducing blocks of cycles at a lower stress than the maximum at which the test is carried out, between the blocks of the major stress cycles. This then gives the crack profile a banded appearance that helps to trace the change of crack profile with the number of cycles during the test.

The techniques of heat-tinting and beach-marking are not universally applicable. In practice most reliance is placed on "reading back" to the size of origin by calculation from the size and shape at the end of the steady crack growth phase. Support for this calculation can be obtained from "striation counting" for certain materials.

TEST ANALYSIS

Predictability

The information required from the test analysis is firstly, was the test result predictable?

Was it consistent with expectations regarding

origin
nucleation life
short crack behaviour
steady crack propagation
rupture

for the stress and temperature conditions imposed?

The first series of questions therefore starts with: "did the crack originate from the predicted feature at the most critical stress-strain-temperature level on the component?" If the answer is "no", to this or any other similar "was it predictable?" question in the routine, the emphasis of the investigation shifts in direction and intensity to "why not?".

Origin

The next questions are "can the origin be located?" and "is its size consistent with the final crack size and crack propagation life estimates?" If the origin is a normal fatigue crack starting from the surface its size may be difficult to define, hence a "reverse" calculation that predicts the origin to be of the size of one or two grains is generally accepted as confirmation of predictability of the result. It is often more reliable to use the crack size at the end of steady growth as the datum, being larger, than the origin. For some materials striation count estimates can be used to support the crack propagation estimates but it must be remembered that these measure the rate of propagation within a grain, whereas the life estimate averages out these local rates round the crack front.

If the material and stress level are consistent with a significant nucleation life, definition of the exact start of steady crack growth may be blurred. This leads to the question of how to interpret the results numerically and how to handle the probability of cracking and failure statistics .

Routine

If the previous part of the analysis suggests that the test result is consistent with expectations (bearing in mind that a significant amount of laboratory data is available before components are tested) the physical investigation continues on routine lines.

Invariably the component surface adjacent to the fatigue crack is examined for machining scores, handling damage, scuffing and fretting if relevant, corrosion, heating discolouration and any other abnormality, as routine. The local grain structure and mode of crack progression is also observed and recorded and the compositional-chemical analysis confirmed.

Anomaly

If at any stage the test result is outside prediction, the investigation pursues the anomaly, though it starts with "were the applied test conditions to specification?". For instance if the origin was not at the surface, why not? Was there a residual compressive surface layer, segregation, an inclusion, a change in structure, what? This involves the entire armoury of laboratory investigation equipment, which has to be considerable. Repeat tests and attempts to repeat the failure are likely. The entire material manufacturing route may have to be audited in trying to trace the variable responsible. Such an investigation becomes an intensive management programme using standard and newly invented techniques specific to the problem.

Mechanism

At the root of all the above is "what is the mechanism by which a crack is formed?".

Experience suggests that a combination of experimental, analytical structural (eg finite element) modelling and probabilistic mathematical research will be required to obtain a satisfactory solution.

The above underlines the importance of being able to model the mechanism of crack formation both qualitatively and quantitatively.

SCATTER EFFECTS

Categories

In making service life predictions scatter may be categorised as follows

- Material behaviour
- Component manufacture
- Cumulative damage estimates
- Stress/temperature prediction accuracy
- Engine performance
- Mission variability

or perhaps even more simply as scatter in

- Strength, life
- Applied loading
- Analytical capability

From the point of view of safety it is as well to remeber that scatter is not limited to material properties and whether the design and service life management procedure chosen is

- Totally probabilisitic
- Damage tolerance
- Retirement for Cause

depends very much on variability and changes of missions and utilisation, design weight goals and initial and maintenance costs and logistics.

Component testing has a role to play in all the above life management procedures. Its contribution to the quantification of material and manufacture related scatter allowances is by

- including all the significant variables in a representative model
- testing a significant volume of material and number of repeated features in order to find the "weakest link" (ie. extreme value function).

Its application in the qualification of stress/strain prediction accuracy is transparent.

FATIGUE BEHAVIOUR MODEL

Scatter in total life (fig.7) is a function of

a) nucleation period

b) structure-related crack propagation

c) size of crack when steady growth starts

d) crack propagation rate

e) fracture toughness

In general, for conventional materials, the characteristic that is least affected by scatter is the crack propagation rate in the steady growth phase, and fracture toughness variability only affects the final stage of crack growth, having very little influence on total life.(Ref.1,3)

The most familiar application of these properties is in estimating propagation life to burst from a nominated size of initial crack eg. related to Non Destructive Inspection capability.

A significant development from the above is to define the maximum initial crack size in a new component from a statistical analysis of test results (ref.5,6).

The concept of a total life (fig.8) made up of

a) a minimum propagation life defined by the maximum initial crack size that can be present.

b) a probabilistic minimum life that incorporates scatter in nucleation phases prior to formation of the maximum initial crack

is consistent with a 3-parameter Weibull distribution, which is very easy to use in practice:

$$p = 1 - \exp [- ((t - t_o)/\eta) ** \beta]$$

In this interpretation, at stipulated stress/temperature conditions:

p = probability of fracture

t = total life to fracture

t_o = crack propagation life to fracture from the defined initial crack

$(t - t_o)$ = variable life to formation of the defined crack

η = "characteristic life", the value of $(t - t_o)$ at $p = 63.2\%$, $1 - \exp [-1]$

** = to the power of

β = Weibull "slope"

The significance of β is that particular values refer to well-known distributions:

Exponential, Poisson, constant failure rate, $\beta = 1$.

Log Normal, $\beta \doteq 2$

Normal, $\beta \doteq 3.44$

Values of $\beta = 2$, $\eta = 1.74$, $t_o = 1$ give a Weibull distribution close to the Log normal distribution used for scatter factors in British Civil Airworthiness Requirements (Appendix C3-2) which has the life ratio of 6/1 between $+3\sigma/-3\sigma$ values. The significant difference is in the Weibull concept that life never falls short of a certain value, whereas with Log Normal there is always a small probability of lives being below the "minus 3 sigma" value.

A particular application of the Weibull model which is important to design and Life Management using Damage Tolerance criteria is its use in defining the maximum size of initial crack that can be in the component. This is of particular significance when this size is below inspection (non-miss) capability.

If sufficient tests are carried out to failure, or well into the steady crack growth phase, the effective (at typical crack propagation rate) initial crack size can be deduced from the size at the end of steady growth for each result. A Weibull plot (fig.9) of the inverse of these sizes provides a cut-off value, which gives the size that will not be exceeded in practice. When this size is below (non-miss) inspection capability, it permits a significantly larger initial service life, possibly as much as the design life, prior to the need for engine removal and strip for inspection. This can have a signficant beneficial effect on the cost of ownership.

If the Weibull plot of effective initial crack size shows two distinct slopes, this can be indicative of a significant nucleation phase, which also is logistically significant if a Total Life procedure is used.

USE OF RESULTS IN COMPONENT BEHAVIOUR ANALYSIS

The use of component test results falls into two main categories

- life management procedure
- diagnostics and research into material behaviour.

Life management

The fundamental role of component testing in a life management procedure is to validate service life predictions, whether these are on the basis of

- total safe life
- damage tolerance
- retirement for cause

Use is made of two major attributes of a properly conducted component test

- the incorporation of all the signficiant variables in a representative model
- the testing of a signficiant volume of material and number of repeated features in order to find the "weakest link" (ie. extreme value function).

that enable the test result to be treated as a statistical sample of component behaviour in the engine. The "minimum safe" behaviour in the engine can then be predicted by making allowances for scatter (as referred to in the above section).

Simplicity

A life management procedure that

a) monitors missions and engine performance by on-board recording equipment.

b) minimises scatter in life prediction by a Linear Elastic Fracture Mechanics approach

has a great deal to commend it on the basis of simplicity.

Component testing can be used to confirm/calibrate crack propagation life predictions from Component Tension, Corner Crack, or other specimens by either

a) introducing artificial notches

b) continuing testing LCF cracks

When artificial notches are introduced, there is scope for testing a significant number of notches, notch shapes and sizes and for covering a number of features during the same test. (Fig.10, ref.4,5).

Total Safe Life

In a Total Safe Life procedure, sufficient components should be tested to (near) failure in order to confirm/calibrate material data obtained from laboratory testing. The "extreme value function" characteristics of the 3-parameter Weibull distribution make this a suitable tool for validating the contents of a material data bank (set of design curves) on the basis of actual/predicted result. This can be used to ensure an adequate margin of safety in predicted minimum safe lives (fig.9).

Research topic

The above highlights a topic for research and mathematical analysis. At present, there is a sound physical basis for LEFM crack propagation life calculation. Data bank design curves based on LEFM predictions do not therefore rely on curve fitting and regression analysis.

S-N curves that include nucleation and structure-related crack propagation lives do have to be produced by "best fit" methods, because the nucleation and early propagation mechanisms have not been successfully modelled mathematically on the basis of physical behaviour. Such a model will be heavily probabilistic because of the dependency on crystallographic structure. Until such models are available the "best fit" S-N curves involving nucleation life will not be quite as satisfactory as those derived from LEFM principles.

Diagnostics

Component testing can be used in the diagnosis of a service or manufacturing problem, simply by virtue of its representational capability. Again, in testing an hypothesis, such as in the development of a new material, it can highlight new or unexpected pieces of information that lead on to research, or more refined diagnosis.

Typical questions that can be asked are:

- is nucleation life significant
- does the crack form as anticipated
- does the crack progress as anticipated
- are surface effects relevant
- is fretting, corrosion, handling damage significant
- is surface treatment necessary, successful
- is the forging route satisfactory
- is the material cleanliness adequate
- is the strain/growth consistent with assumed constitution relationships

The answers may be simple, or indicate the need for research, but invariably lead to a better understanding of material behaviour in component form.

FUTURE USE OF COMPONENT TESTING

Component testing will continue is its current role of providing a comprehensive model of significant variables, until/unless sufficient is known about each individual variable to permit a mathematical life model of the component to be built up from the separate characteristics in as reliable and cost-effective manner.

Better mathematical models of material manufacture, the forging and heat treatment processes, residual stresses and behaviour of discontinuities will however be of considerable assistance in selecting and developing materials with the required characteristics and may reduce the total of component tests needed to support and calibrate a material data bank.

Component testing will continue to be used as an integral part of the development of a new material. With new materials, dual alloy and in particular composite ceramic discs, component testing is likely to be the only way of making sure that the anticipated characteristic are achieved and the probability of failure in service minimised.

The Life Management goal is "making sure" and Component Testing is one of the most powerful tools.

GENERAL SUMMARY

Component testing performs a major role in design and life management and by virtue of

- representation of engine conditions
- incorporation of all the significant variables
- the testing of a significant volume of material and number of repeated features

is one of the most powerful tools available in ensuring that design and life goals are met.

Component testing is integrated with laboratory investigation and material data generation to provide a material data bank that can reliably be used for design and service life prediction. Modern techniques of stress and fracture mechanics analysis, crack monitoring and metallography and probabilistic approaches are employed. The understanding of material behaviour in component form that is built up following this approach, in which component testing can be used in a diagnostic or research role, leads to the development of new and improved materials.

ACKNOWLEDGEMENTS

The author wishes to thank Rolls-Royce plc for permission to present this paper and the data that it contains. Appreciation is also expressed to colleagues in the Materials and Mechanical Technology and Operational Research departments for their co-operation and support.

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LIFE ESTIMATION, VALIDATION AND MANAGEMENT

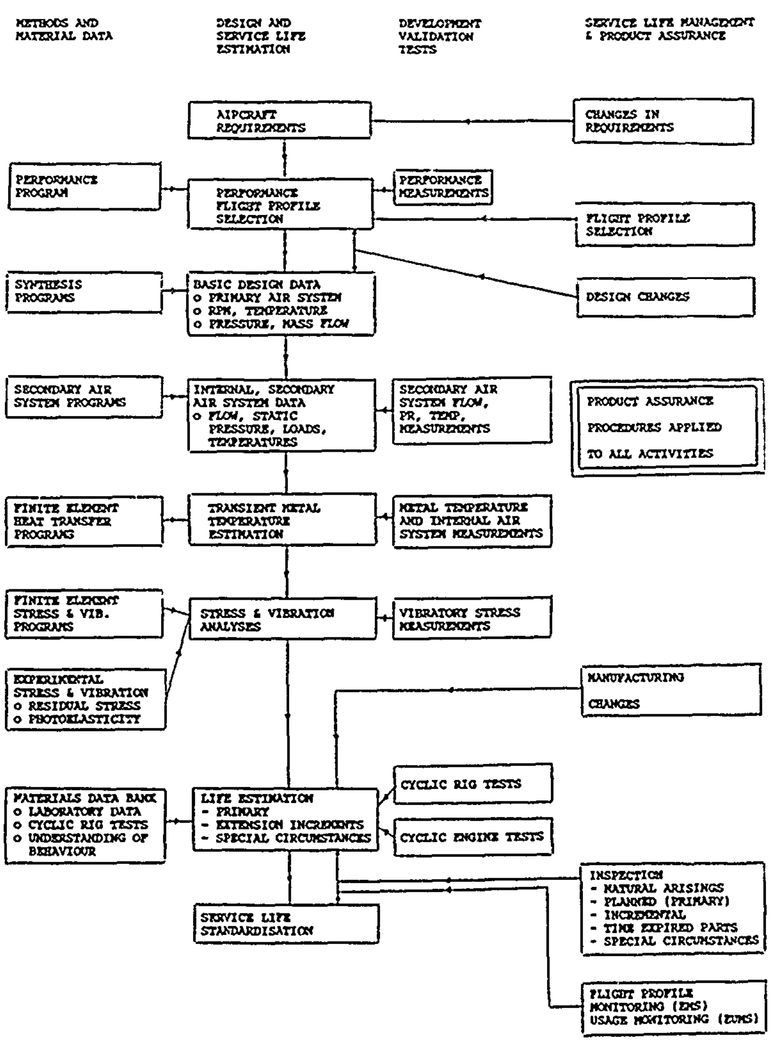

FIGURE 1

Vertical cyclic spinning rig

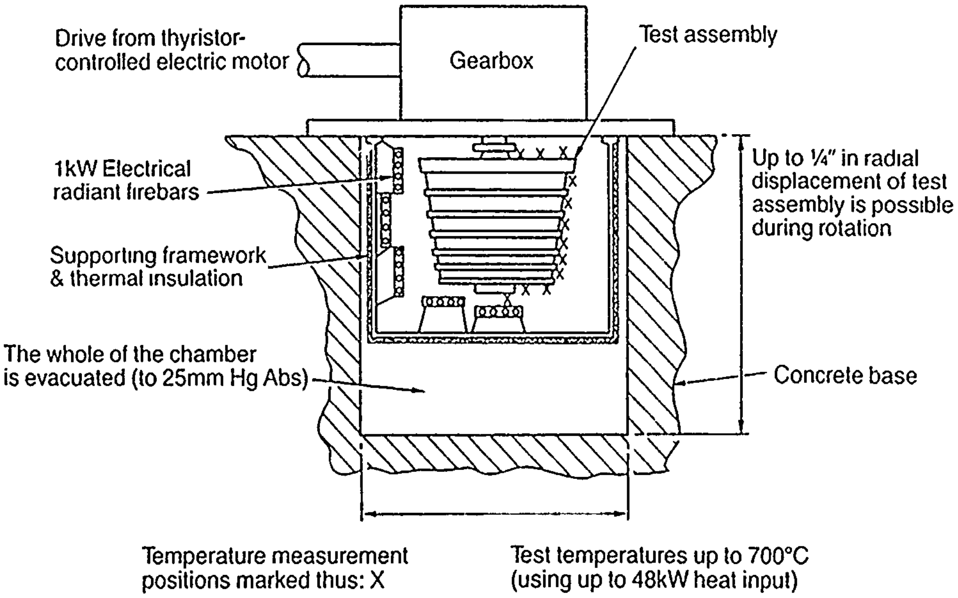

FIGURE 2

VML 51563

Compressor rotor features

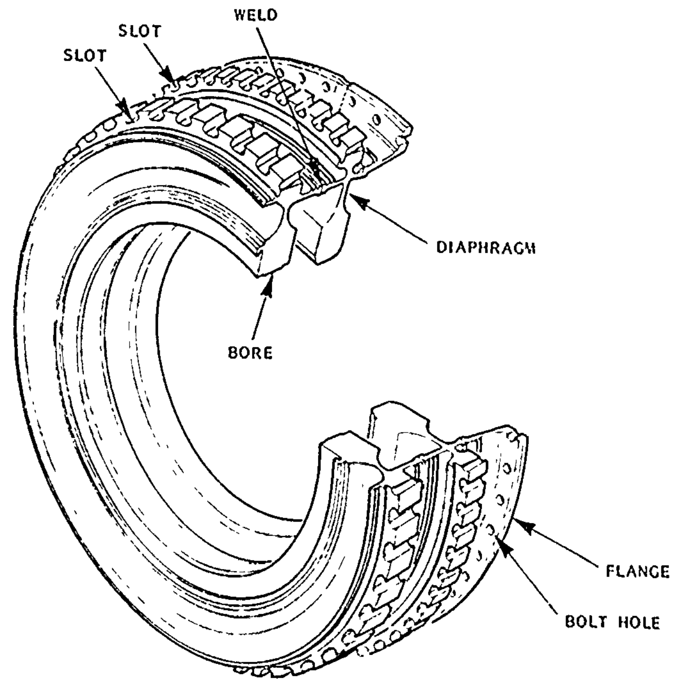

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FIGURE 3

Turbine disc features

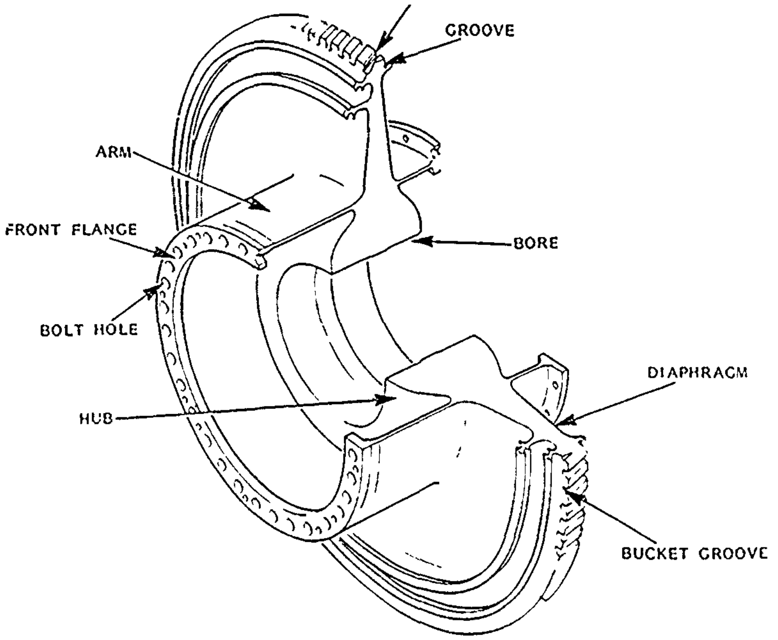

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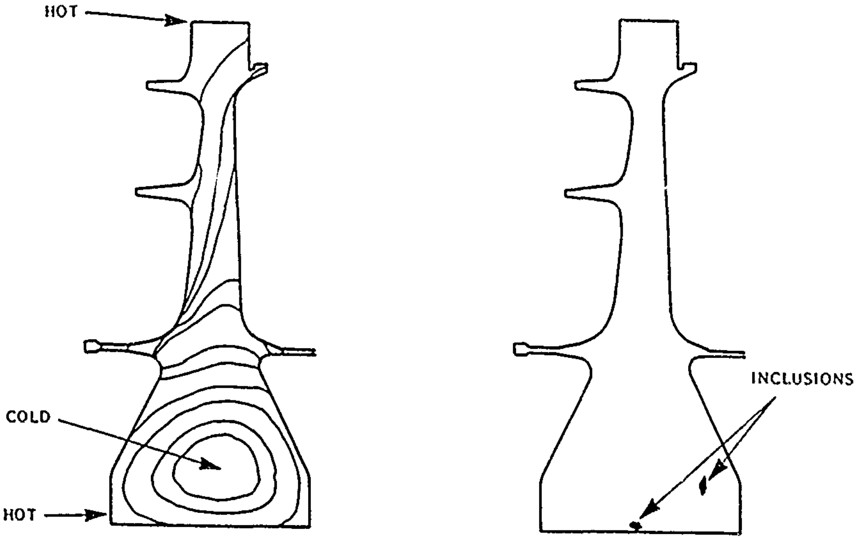
FIGURE 4

Transient thermal stress in centre cob



TEMPERATURE CONTOURS

COMPONENT TESTS WITH INCLUSIONS - USED TO CLEAR LIFE

FIGURE 5

VML 51566

Uniaxial load test

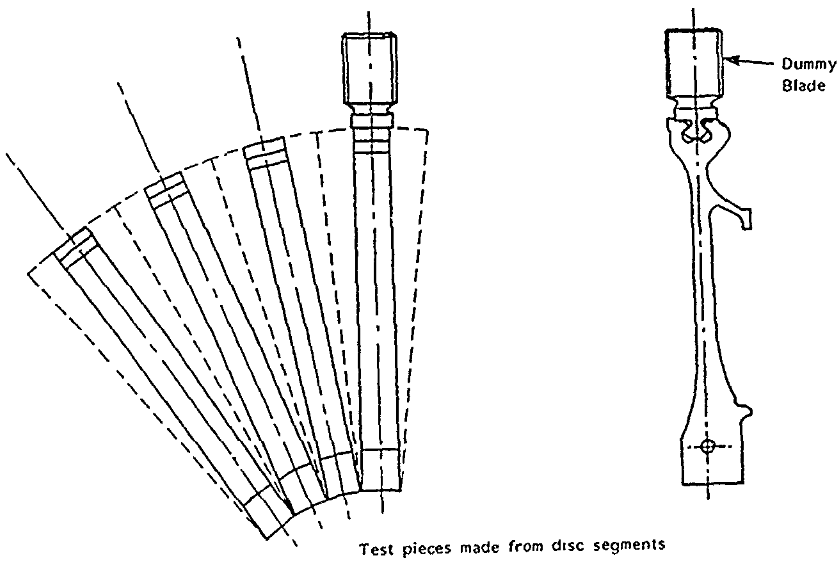


FIGURE 6

VML 51567

Fatigue behaviour model

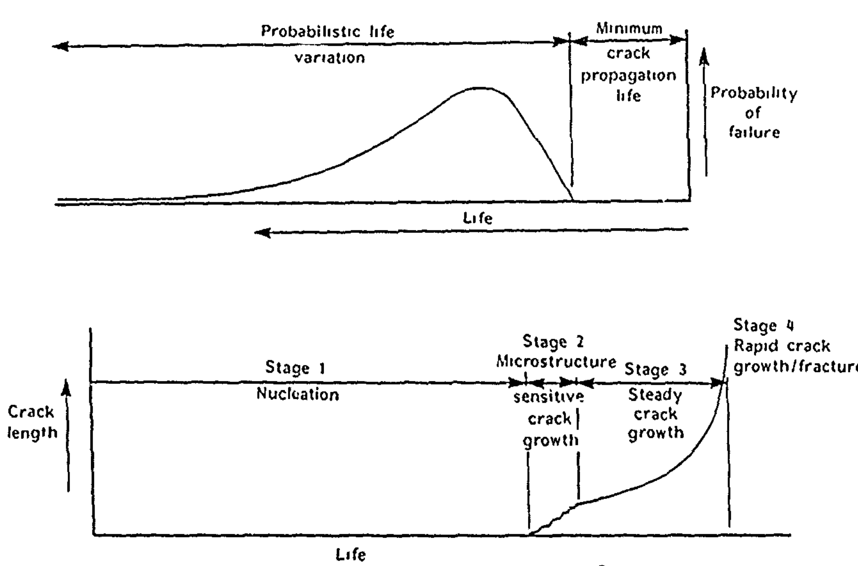


FIGURE 7

VML 51568

Weibull plot

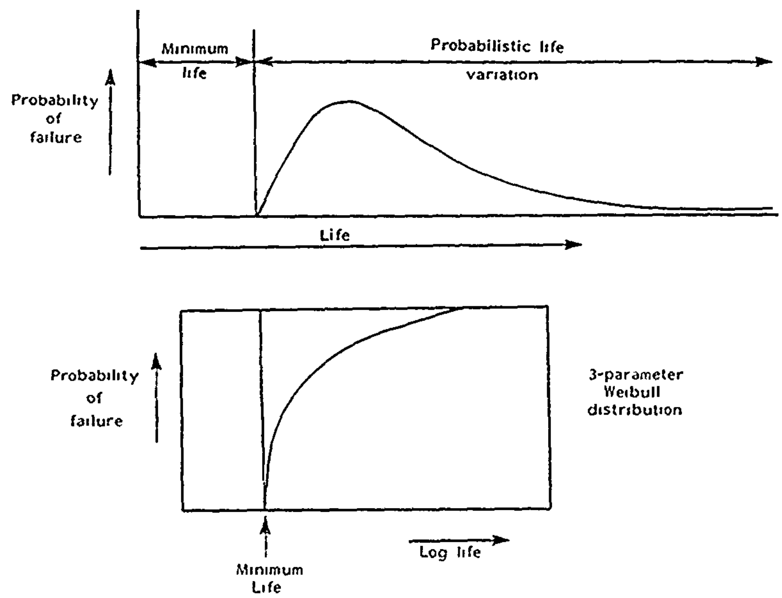
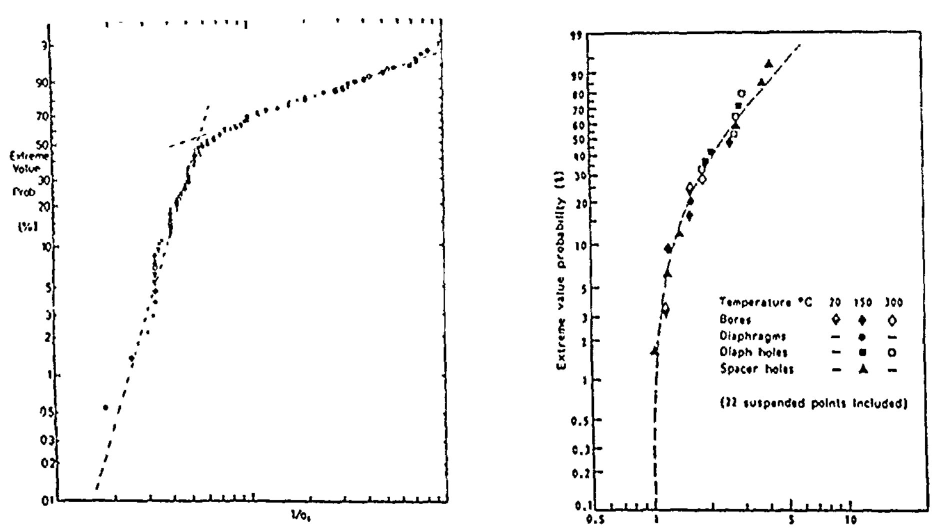


FIGURE 8

VML 51569

Applications of Weibull



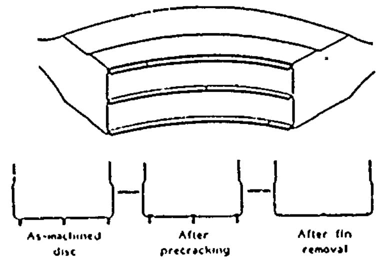
Ti 6Al 4V Full Effective Initial Crack Size Distribution

Ti6Al4V Comparison of predicted and actual lives

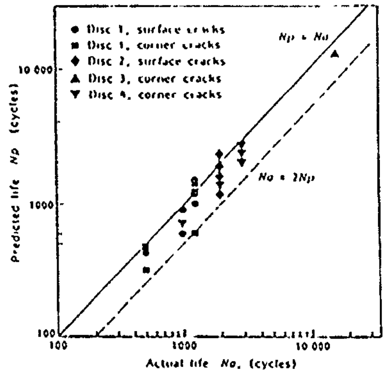
FIGURE 9

VML 51570

Artificial crack propagation tests



Rolls Royce disc bore fin crack testpiece



Bore crack propagation results for artificially cracked Ti 6-4 discs

FIGURE 10

VML 51571

LIFE VALIDATION ROUTES

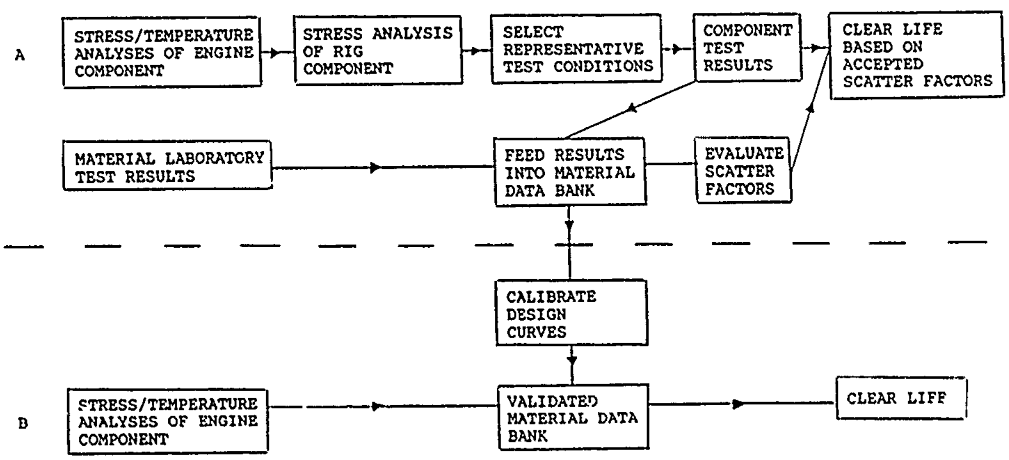


FIGURE 11

A - "DIRECT"

B - "DATA BANK"

THE ROLE OF INFLIGHT ENGINE CONDITION MONITORING ON LIFE CYCLE MANAGEMENT OF CF-18/F404 ENGINE COMPONENTS

by

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ABSTRACT

The Canadian Forces have developed an Engine Parts Life Tracking System (EPLTS) to facilitate effective On Condition Maintenance (OCM) of the CF-18/F404 engine. The system tracks 64 parts and modules on the basis of 8 Life Used Index values (LUIs) defined by the engine manufacturer, General Electric (GE). The LUI values are obtained by the Inflight Engine Condition Monitoring System (IECMS) in the mission computer onboard the CF-18 aircraft. The EPLTS database is updated daily to provide an up to date status of all engines in the fleet.

This paper describes the organization of EPLTS and details the parameters being monitored. Various EPLTS capabilities, with respect to critical part life management and analysis, are then reviewed.

INTRODUCTION

Upon acquisition of the CF-18 fighter and its General Electric (GE) built F404 engines, the Canadian Forces (CF) was faced with the task of establishing an efficient method of overhaul for the engine. Traditionally, the service life of engines has been specified in terms of engine flying hours, with the life limit being defined on the basis of the most severe operating environment. In military aircraft the severity of the mission varies greatly; consequently, under traditional engine maintenance, parts are often retired from service prior to being life expired. To avoid such unnecessary expenses while still providing a high degree of safety, the CF have adopted an On Condition Maintenance (OCM) philosophy for the F404 engine. The OCM concept, established by GE, allows an engine to operate as long as individual components have not exceeded their life, service or performance limits.

The OCM concept is generally applied to components where maintenance techniques such as borescoping, radiography, oil analysis and vibration analysis can reliably detect incipient failure modes. It is also used for components where secondary effects of a particular failure mode do not compromise safety or mission completion capability. In turbomachinery, failure modes associated with low cycle fatigue (LCF), thermal fatigue or stress rupture are not easily detected by the usual techniques [Ref. 1]. In general, the secondary effects of such failure are also unacceptable. Consequently, the life limits must be based on somewhat less tangible parameters such as LCF cycles, equivalent full thermal fatigue cycles (EFTC) and time above a certain operating temperature (stress rupture factor, SRF). To be effective, however, the service life history of all critical components making up an engine must be known.

To this end the CF have implemented an Engine Condition Monitoring (ECM) system for the F404 engine. The central feature is a computerized Engine Parts Life Tracking System (EPLTS) which facilitates effective OCM on these engines. This paper describes the organization and capabilities of EPLTS and presents examples of uses of the data.

F404-GE-400 ENGINE AND EPLTS

The F404-GE-400 is an augmented low bypass turbofan engine. The engine is of modular construction, consisting of six major engine modules, and a number of accessories mounted external to the engine. The six modules comprising the F404 engine are (Fig. 1) :

- Fan Module
- High Pressure Compressor Module
- Combustor Module
- High Pressure Turbine Module
- Low Pressure Turbine Module
- Afterburner Module

These modules are readily interchangeable between other engines or with spares. If one module contains components that have reached their life limit or have become defective, the module can be removed and replaced with one that is serviceable, without any need for engine trimming. Engine operation is however verified, prior to installation in the aircraft. This allows simple module replacement to become the primary mode of maintenance. Subassemblies such as rotors, or other components within modules can be removed and replaced in a similar fashion.

Over a period of time, different engines will have undergone different service lives, but some of their parts or modules will have been moved between engines or replaced by new parts. With time, an engine will become a mix of components with varied life histories.

The task of CF-18/F404 EPLTS is to ensure that components are not used beyond manufacturer-specified life limits, while extracting maximum possible component usage. Since engine overhaul is scheduled only when certain operational life limits are reached, in theory aircraft availability should be increased.

USAGE MONITORING

The capability for service life or usage monitoring is made possible by an advanced and fully integrated Inflight Engine Condition Monitoring System (IECMS) developed by the engine manufacturer. The system monitors engine parameters continually and computes life usage parameters inflight. Additionally, the system activates cockpit cautions and sets maintenance codes in the event of an exceedance e.g. engine overtemperature. During inflight 'incidents', 5 seconds of pre- and 35 seconds of post-event engine data may be recorded on pilot demand or by direction of the mission computer (whenever a limit is exceeded) [Ref. 2]. In addition, a 20 second history of engine mechanical condition and performance related data are recorded during pre-takeoff thrust checks.

The service life history of each component is tracked on the basis of Life Used Index (LUI) values which are recorded by IECMS. The LUIs tracked are :

EOT Engine Operating Time
SRF HP turbine blade stress rupture factor
N2F Rotor speed low cycle fatigue - full cycle
N2P Rotor speed low cycle fatigue - partial cycle
P3F Compressor Delivery Pressure LCF - full cycle
P3P Compressor Delivery Pressure LCF - partial cycle
EFT Equivalent full thermal cycle count
TAMP Time at or above intermediate power

The above LUIs are recorded shortly after initial power up and again upon completion of the mission. The difference indicates life usage (mission severity) during the flight.

The low cycle fatigue oriented LUIs have been used extensively in predicting life limits on the rotating components. In the cold section, these alone provide good estimates of life usage. In the hot section, engine life is closely associated with temperature and RPM, even when the engine is operated within allowable limits. Hot Section durability depends strongly on the 'time-temperature-RPM' relationship within the engine. The primary factor responsible for life consumption is temperature,although all three are important [Ref. 3]. The two LUIs SRF and TAMP provide added input into the severity of the missions 'weathered' by the engine hot section components.

The LUIs were defined by General Electric in the development of the IECMS system. Of particular interest is the Equivalent Low Cycle Fatigue (ELCF) count. The ELCF is a derived value defined as :

$$ELCF = N2F - KFAC\ (N2P - N2F)$$

where the KFAC is an analytically derived constant unique to each part and defined by General Electric.

SRF is an indication of the amount of time the High Pressure Turbine spends at high temperatures. The blade metal temperature is estimated by the IECMS algorithms by combining engine inlet temperature, altitude and engine exhaust temperature (EGT). At high altitude/low Mach number, the low EGT levels result in low blade temperature. As a result SRF accumulation is slow. In contrast high speed low altitude flying causes much faster SRF accumulation [Ref. 4] This parameter is thus very useful in identifying severity of life expenditure in various parts of the aircraft flight envelope.

EPLTS ORGANIZATION

Data are entered into EPLTS at two levels, Fig. 2. The system operates in a spoked hub configuration. New engine and component data are entered at the centralized NDHQ (National Defense

Headquarters). This data are then made available to the nodes. At the main operating bases (MOB's), the nodes feed information concerning modifications of engines, configuration changes and life usage. The data are stored in approximately 90 tables linked through a relational database [Ref. 5]. The database management system supporting EPLTS is ORACLE.

The database can be interrogated from any node using the user friendly Structured Query Language (SQL). Several general interrogation programs have been written in higher level languages such as Report Writer, Pascal, and Fortran for added ease of access to the data tables.

As the Aircraft data storage tape becomes full, the data (which includes EPLTS data) are downloaded from the aircraft to the base computers. The Base EPLTS database is updated and a file is sent to update the NDHQ database. At NDHQ cumulative statistics are then calculated.

EPLTS DATA

The data stored in EPLTS consists mostly of the field history of each engine as well as accumulated usage and service status of the tracked parts. There are 24 individual items which are assigned life limits. Another 28 'high cost items' (parts, subassemblies) are designated for OCM [Ref. 6]. The engine comprises 11 modules/assemblies which are themselves tracked by the system. Each part is identified by a part number as well as a specific serial number.The part number identifies the general configuration of a particular product from the manufacturer while the serial number identifies a particular component amongst all components with the same part number.

To facilitate reference to parts and modules of interest, a work unit code (WUC) is used. A list of these can be found in Fig. 3. [Ref. 7]. This list also identifies all the parts that are tracked and those that have manufacturer specified life limits.

Each part also has assigned to it a next-highest-serial-number (NHSN) and a highest-serial-number (HSN) which help define its present state in relation to higher assemblies. For instance if a compressor rotor has a NHSN of a compressor module and a HSN of a whole engine, the rotor is fully assembled and installed in an engine. If, however, the HSN is only that of a compressor module, it is evident that the module is uninstalled.

EPLTS CAPABILITIES

The capabilities of the EPLTS are very widespread, with new applications being conceived continuously. Here, some of its more frequent uses will be outlined.

Logistics Planning

EPLTS was principally designed to track accumulated life usage of selected engine components in terms of 8 life used indices. Furthermore, EPLTS has the capability to verify and enforce component compatibility during overhaul and parts replacement and maintain an up to date status of every engine in the fleet through maintenance records. Engine status, indicating whether or not manufacturer specified engine inspections and modifications have been carried out, are also stored within the EPLTS system.

Through tracking of all parts and modules as well as engines, the system is capable of providing vital information for planning parts procurement and deliveries. In particular, a secondary program entitled the Logistics Planning Module (LPM) allows planning of maintenance arisings using a window concept. When replacement modules are selected to be placed into service, a check is carried out to ensure that the modules will not require attention until the end of the next service window. At present, a nominal window (i.e. 400 EOTs) is set by the engineering authority for the engine parts changeout. Parts which fall within this window may be removed. Where life limits are defined by a LUI other than EOT, a conversion factor is applied to the LUI to estimate roughly how long it will last in terms of EOT. This conversion factor is defined on the basis of the previous year's flying, with each base having its own set of conversion factors. This is done to account for the inter-base differences of mission definitions.

Maintenance planning is carried out on an engine basis whereby one can focus on the probable service actions that a particular engine might expect to see in the future. Alternatively, analysis can be conducted on a monthly basis to estimate the shop visit rate at a particular base. This permits prediction of required inventory items for the forthcoming months. The present system is set up to run on a 60 month time frame thus permitting long term planning for procurement of long lead time items.

EPLTS provides easy information access through numerous preformatted screen displays, reports and stagger plots for such purposes as inventory status, life usage, maintenance history, etc. The system is very flexible, permitting direct user access via the ORACLE query language.

DATA ANALYSIS

EPLTS offers the capability for monitoring and managing component usage and can handle large quantities of data with ease, speed and accuracy. A relative assessment of various mission severities is readily available at NDHQ. For example, average LUI accumulation per mission over a six month period at a Base are presented in Fig. 4. Such data representation is useful for identifying the relative severity of missions.

While EPLTS allows swift access to and preliminary analysis of engine usage data on a mission-by-mission basis, the statistical nature of the data demands careful analysis and interpretation. This is because the data are non-normal. The third and fourth moments about the mean of virtually every LUI exhibit significant skewness and curtosis. The standard deviation of the raw data, for each LUI for various mission types is also presented in Fig. 4.

The quality of the data depends on the precision of the IECM system. An assessment of IECMS related precision errors of selected engine parameters are presented in Ref. 8. The evaluation was accomplished using a test cell data acquisition system of known precision at the National Research Council of Canada. The parameters and calculated sensor errors are presented below along with estimates of the resolution of the on board data system (MSDC) :

TABLE 1
PRECISION OF SELECTED PARAMETERS
(BASED ON TWO STANDARD DEVIATION CONFIDENCE LIMITS)

PARAMETER	ENGINE SENSOR PRECISION (%)	MSDC PRECISION (%)	MSDC DIGITAL RESOLUTION(%)
Inlet temp	0.037	0.44	0.37
Fan rotor (RPM)	0.087	1.45	0.15
HPC rotor (RPM)	0.051	0.97	0.11
Comp. delivery press.	0.335	0.65	0.24
Exhaust gas press.	0.261	0.44	0.17
Exhaust gas temp.	0.072	0.22	0.12

In general, it was observed that the Maintenance Signal Data Converter (MSDC) was a significant source of precision error. But, IECMS data repeatability can be improved by increasing the MSDC digital resolution for each parameter. An examination of the IECMS algorithm reveals that of all the LUIs, SRF and EFTC are most sensitive to the calculated blade metal temperature. The precision errors for inlet and exhaust gas temperature correspond to 3-7% in EFTC and 6-13% precision error in SRF counts [Ref. 9].

The variation in EFTC and SRF accumulations for a given mission, and between different missions are much larger (Fig. 3). As long as sensor error and noise are eliminated, there is little danger that mission to mission variations are masked by IECMS precision errors. At the present time however, there is little information on the variation of precision and bias errors of aircraft instrumentation with usage.

With readily available desk top computing power, it is tempting to analyze the raw data with easily accessible software packages. However, even simple multiple regression of the raw data, to characterize mission profiles, requires caution.

Although there are few restrictions in performing multiple regression on several variables, the estimates of confidence intervals for the regression coefficients require several assumptions. It is frequently assumed in multiple regression that the independent variables are controlled and without any underlying distributions. Where a distribution must be assumed, it is expected that the independent variable will be normally distributed [Ref. 10]. It is assumed that the errors about the regression surface are normally distributed with equal variance in the range of interest. The effects of non normality on sample correlation coefficients are especially pronounced.

It is essential that the sample data be assessed for outliers. Whether the data are a heavy tailed distribution (e.g. Cauchy) or a contaminated normal distribution, points that lie at a distance from the body of the data can greatly influence the regression coefficient estimates [Ref.11]. Outlier detection schemes that are available in common software packages are based on the common least-sum-of-squares (LS) estimate. By definition, LS tries to avoid large residuals. Consequently, LS estimates try to accommodate outliers at the expense of the remaining observations. There exist alternate methods for data analysis e.g. outlier detection by robust regression, cluster analysis, non-parametric statistics etc. that may allow more meaningful data reduction. These techniques are currently being examined.

COMPONENT LIFE PREDICTION

The life limits for critical components specified by the engine manufacturer are usually determined on the basis of complex analytical calculations and later verified by spin-pit tests and factory engine tests. In some cases however, the life prediction model may not be entirely representative of the type of missions flown by a specific user. If the actual missions are more severe, premature component failure may occur.

Several such failures could perhaps remain "unexplained" in the absence of an EPLTS data base. In contrast, the wealth of information available through a parts life tracking system as described here might permit the user to pinpoint the reasons for accelerated damage accumulation and failure. As the user's information on damage modes and severity of damage observed in service for tracked components builds up, several new trends may be detected between this information and the EPLTS database. For example, if a component tracked on EOT is operating at a substantially higher temperature than originally designed for, a LUI such as TAMP or SRF may provide much better correlation with service experience. Thus the user has the option of choosing an alternative LUI or combination of LUIs for safer, more economical fleet maintenance.

COMPONENT REPAIR AND OVERHAUL

At present, Orenda is developing a series of comprehensive repair and life extension schemes for various life limited components in the F404 engine. Depending on the repair or life extension technique used, a repaired component may behave quite differently from a new part. The fracture critical location may be altered and the rate at which service induced danage accumulation or life usage occurs may be substantially different from that in a new component. The LUI upon which a repaired components is tracked may not even be the same as in the case of a new component.

Thus, to be able to safely use repaired critical components that are life limited, an EPLTS database is essential. Without it, maintenance of repaired critical components on a simplistic basis of engine flight hours may lead to catastrophic results.

CONCLUSIONS

The Engine Parts Life Tracking System developed by the Canadian Forces to facilitate OCM on the F404 engine has been successful in satisfying its mandate. Problems encountered during the setup phase (eg. software modification for to enable efficient data collection) have been resolved. Remaining complications (eg. improved EPLTS generated reports) are being addressed concurrent with the operation of the system. Particular attention is being given to determining the effect of usage on precision and bias errors of aircraft instrumentation.

The ability of EPLTS to manipulate large volumes of data with speed and accuracy has resulted in some unanticipated but beneficial uses of the data. EPLTS data applications have benefited the CF by facilitating component repair and life analysis, usage monitoring, and logistics planning in the maintenance of the F404 engine. Without EPLTS, maintenance of the F404 would be a monumental task.

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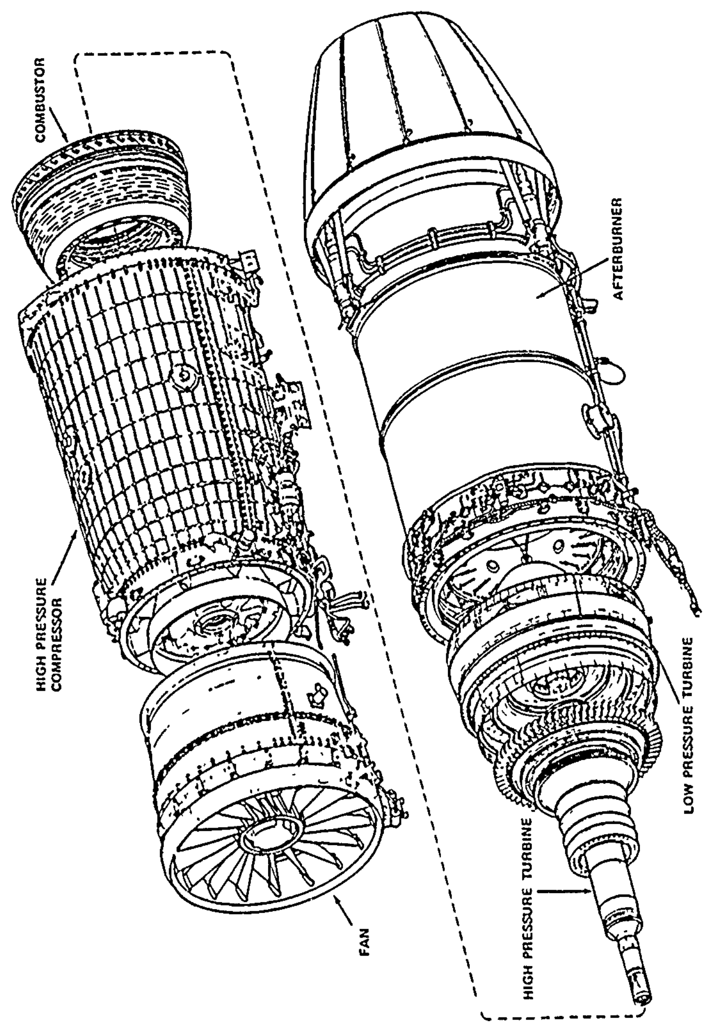

ENGINE MODULES

Fig. 1

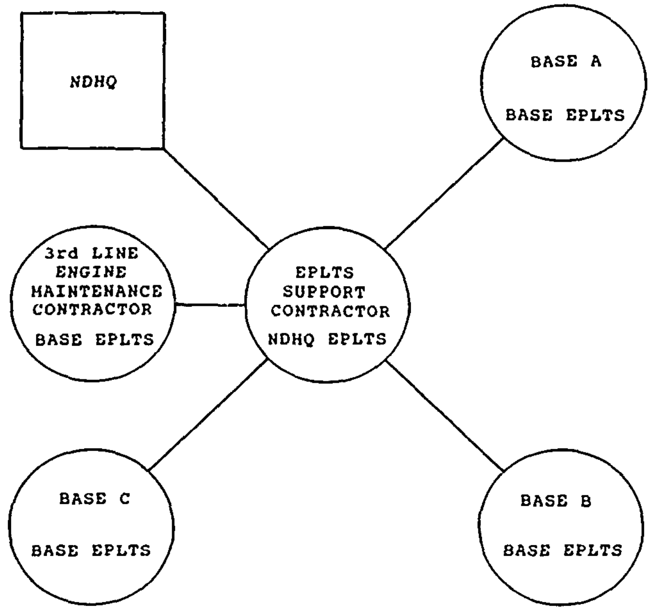

Fig. 2

CANADIAN ARMED FORCES
F404-GE-400
CONFIGURED ITEMS/PARTS
TRACKED BY
ENGINE PARTS LIFE TRACKING SYSTEM

WUC		
BE	ENGINE ASSEMBLY	M
BEA	FAN MODULE	M
BEAB	FAN ROTOR ASSY	M
BEABA	STG 1 FAN DISK	L
*BEABB	STG 1 FAN BLADE (INDIV)	L
BEABXXX	STG 1 FAN BLADE (SET)	L
BEABD	STG 2 FAN DISK	L
BEABF	STG 3 FAN DISK	L
BEABG	STG 3 FAN BLADE (SET)	O
BEABJ	REAR FAN SHAFT	L
BEABN	NO 2 BRG INNER	O
BEAAF	NO. 1 BALL BEARING	O
BEAA	FRONT FRAME ASSY	O
BEB	HPC MODULE	M
BEBD	COMPR ROTOR ASSY	M
BEBDA	STG 1-2 COMPR SPOOL	L
BEBDB	FRONT SHAFT	L
BEBDC	STG 3 COMPR DISK	L
BEBDE	STG 4-7 COMPR SPOOL	L
BEBCF	NO. 3 BALL BEARING	O
BEBCB	NO. 2 OUTER BEARING	O
BFBF	COMBUSTION CASE	L
BEGG	FUEL NOZZLE SET	L
BEBA	MID FRAME	O
BEBE	COMPRESSOR STATOR ASSY	O
BEBEA	COMPRESSOR FORWARD CASE	O
BEBEL	COMPRESSOR AFT CASE	O
BEC	COMBUSTOR MODULE	M
BED	HPT MODULE	M
BEDA	HPT ROTOR ASSY	M
BEDAA	HPT FWD SHAFT	L
BEDAH	HPT REAR SHAFT	L
BEDAC	FWD ROTOR AIR SEAL	L
BEDAD	FRONT COOLING PLATE	L
BEDAG	AFT COOLING PLATE	L
BEDAE	HPT ROTOR DISK	L
**BEDAF	HPT BLADES (INDIV)	O
BEDAXXX	HPT BLADES - SET	L
BEDD	FAN DRV SHFT ASSY	L
BEDE	NO. 4 ROLLER BRG	L
BEE	LPT MODULE	M
BEEM	LPT ROTOR ASSY	M
BEEMD	LPT CONICAL SHAFT	L
BEEMA	LPT ROTOR FWD SEAL	L
BEEMB	LPT ROTOR DISK	L
**BEEMC	LPT BLADE (INDIV)	O
BEEMXXX	LPT BLADE SET	L
BEENC	NO. 5 ROLLER BRG	O
BEEN	EXC FR&C-SUMP ASSY	O
BEF	AFTERBURNER MODULE	M
BEFB	AFTERBURNER LINER	O
BEND	ANTI-ICING VALVE	O
BEGC	MN FUEL CTRL ASSY	O
EBAD	ELECT CTRL ASSY	O
BEGB	MN FUEL PUMP ASSY	O
BEJK	CIT TRANSMITTER	O
BEQ	ACC GEAR BOX	O
BEBB	POWER TAKE OFF	O
BEKA	VEN PWR UNIT ASSY	O
BEHC	LUBE PUMP ASSY	O
BEGK	A/B CONTROL ASSY	O
BEGJ	A/B FUEL PUMP ASSY	O
EBCC	T5 HARNESS	O
BEJF	FAN ACTUATOR ASSY	O

LEGEND

Modules/Assemblies	(M)	11
Life-Limited	(L)	25
On-Condition	(O)	28
Total		64

* BLADE table

** Dummy records in BLADE table for software processing purposes only

Fig. 3

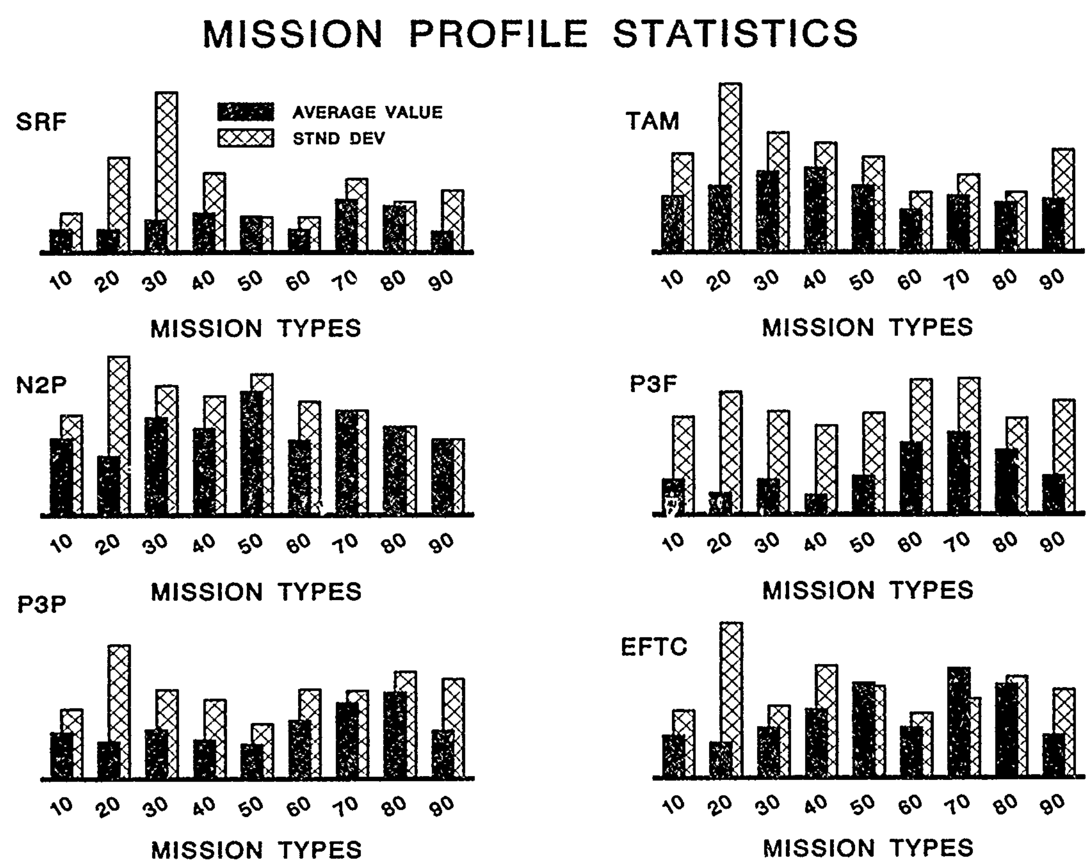
MISSION PROFILE STATISTICS
SRF
AVERAGE VALUE
STND DEV
10 20 30 40 50 60 70 80 90
MISSION TYPES
TAM
N2P
P3F
P3P
EFTC

Fig. 4

LIFE MANAGEMENT PLANNING

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SUMMARY

Structural integrity and safe operation of gas turbine engines for commercial aircrafts has been gained through the application of a life management procedure, which combines state of the art technology from various disciplines of engineering. The core of the process is substantiation of components and their materials for low cycle fatigue / mission life and it is essentially based on Safe Life Approach (SLA) design. Fracture mechanics analyses are also applied in some cases for proper understanding of the behaviour of materials susceptible to fatigue crack growth. In this paper, the life management procedure is discussed. Basic lifing process on the basis of SLA and application of fracture mechanics are also presented.

1. INTRODUCTION

Structural integrity of commercial gas turbine engines is based on the application of a life management scheme, which takes into account safe operation of individual critical components in view of the engine application and flight mission. In this approach, each critical part is identified with a unique number, indicating its production batch. Each batch of component is then substantiated to yield a safe operation during its service lifetime. Any change in the production batch, which may arise from different forging heat treatment or other similar deviations, are also accounted for, in order to ensure that the minimum safe life is achieved in the field The system essentially specifies one life for one batch of components Any other changes to any one of the component configuration, temperature, r.p.m or material will change the part idendification and hence the part will undergo a new substantiation. The determination of components' service lives stems from a Low Cycle Fatigue (LCF) system, which empirically relates specimen / hardware test experience to the calculated and observed design parameters In general design of a part from an idea to the final secured drawings consists of various design moves and iterations In each iteration, many engineering disciplines such as aerodynamics, structure analysis, dynamic analysis, hardware design, manufacturing, material development and fabrication may be involved. In each cycle the performance of the part is assessed from both aerodynamic efficiency and structural integrity points of view. Basic and typical lives of components are based on a Safe Life Approach (SLA), whereby the design criterion is based on the probability of a 800 μm (1/32") crack formation at the end of the service life of the component. Fracture mechanics analyses are often used to obtain component lives to this crack size, once these components have developed cracks during rig tests In addition, fracture mechanics analyses are used to assess the remaining lives of the uncracked components in order to establish their margins of safety.

In this paper, an overview of the life management is presented and some of the terms representing the steps in the lifing process are defined and discussed. Analytical life prediction methodologies used in this life management process are Safe Life Approach (SLA) design and fracture mechanics analyses for predicting crack growth lives. Both methods are also discussed in some detail and their application is demonstrated using a fan disc stress analysis and test data.

2. LIFE MANAGEMENT PLANNING

Life management planning is referred to the entire process of lifing an engine critical component from the design stage to the point, where the engine is installed for a specific operator. This process is briefly outlined in the block diagram of Fig. 1. The process is used to establish a service life for each critical component for a particular application. The service life is primarily a function of its installation and usage It is affected by the misssion profile, operator's specific requirements and future deviations from the initially agreed requirements. None of these factors are known during the design and development of the engine and hence, as it is seen from Fig 1, the initial lifing of the components is based on a Basic Cycle (see also Fig. 2). The basic Cycle is a base line mission, whereby the engine is brought from rest to idle condition, then stabilized and accelerated to a maximum condition and again stabilized. It is then decelerated to idle and again stabilized and finally brought to rest. The idle and the maximum conditions, in this mission, are specified as a reference for each engine type and are not necessarily the engine running conditions. The basic life is then, the predicted maximum allowable number of basic missions for safe Low Cycle Fatigue (LCF) life. As already mentioned, the design and development of the engine is based on the Basic Cycle LCF life Once the mission profile and other specific requirements have been defined and some field experience has been gained, then the engine parts are reassessed and lifed based on the Typical Mission (see Fig. 1). A Typical Mission is usually referred to a flight progressing from engine start to engine stop as shown in the example of Fig. 2. In general, a Typical Mission can be a composite of two or more Specific Missions. Specific Missions, in turn, are referred to a flight from engine start to engine stop, representing a specific ' operator's particular conditions ' for a repetative flight condition. The Typical Mission life is the predicted maximum allowable number of Typical Missions for safe LCF life. This life is calculated on the basis of rain flow cycle partitioning technique and linear damage accumulation (Miner) rule. The latter is further substantiated by spin pit testing of critical components under conditions that simulate engine loads.

As it is seen in Fig. 2, the Typical Mission life is further reviewed based on the field experience and refinement of the actual mission. Then a Service Life is recommended and included in the Table Of Limits (TOL) The final Service Life is equal or smaller than the Recommended Service Life and is included in the engine Service Bulletin. The factors that are considered to arrive at the Service Bulletin life are usually normalized in the form of Flight Counts and Flight Count Factors (FCF). Flight Count is the accumulation of total flights, where each flight comprises a lift - off to touch down, irrespective of engine starts and stops multiplied by the appropriate FCF. The FCF itself is a measure of number of Full Cycles in each flight, ie. the cycles consisting an engine start, a lift - off to touch down followed with an engine shut down. The FCF is modified for the cases, where there exists several flights per engine start. Helicopter operation is an example of such cases. Another factor that is used to arrive to the Service Bulletin life values is referred to as the Certainty Factor and it indicates the level of technology used to establish the component's life. Such factors are intended to give a measure of the confidence, with which the quoted lives can be used in setting engine ' Time Between Overhauls ' and assessing engine maintenance costs. The Certainty Factors are derived from several observations, such as actual lives confirmed by field experience, residual LCF data obtained from testing crack free parts that have been retired from service and testing engine parts under realistic engine operating conditions Other items influencing the Certainty Factors deal with analytical methods using material

LCF properties,which are established from material specimen and sub-component tests. In this manner, the Certainty Factors are deemed to account for the errors that may have been arisen in the analytical methods used and the assumed enviromental conditions. They further ensure safety margins for the cases, where field experience has not been accumulated and component rig tests are used, which may not fully represent engine operating environment. The LCF life prediction of the critical components stems from the SLA and applications of fracture mechanics analyses The baseline lifing system in the SLA design are continuousley revised to reflect field experience as well as specimen and component test data (see Fig. 1) SLA and fracture mechanics anlalysis methods are discussed in more detail in the following sections of this paper.

2.1 SAFE LIFE APPROACH (SLA) DESIGN

An overview of the SLA has already benn discussed in [1]. It was mentioned in this reference that the basic requirements for LCF lifing of P&WC engine components consist among others, establishment of reliable calculation methods. The calculation methods comprise two and three dimensional stress analyses, heat transfer analysis, Foreign Object Damage (FOD), containement, mission and LCF life analysis. These analyses, depending on their nature are carried out for transient and steady - state conditions. In the present paper, application of the SLA design and fracture mechanics to a fan disc is presented whereby, some of the above analyses methods are addressed in more detail.

A 3-D finite element grid of the fan disc / blade assembly made of Ti6Al-4V material is shown in Fig. 3. Elastic stresses were computed using a 3-D substructure code Contact effects between the blade fixing and disc dovetail slot were also included in the model using the ' Gap elements [2] as shown in Fig 3. Distribution of the elastic stresses under maximum load conditions of the Typical Mission is shown in Fig. 4a, indicating that the lower edge of the disc / blade contact area is critical. Fig. 4 corresponds to the leading edge of the disc. Bivariate elastic stress field on the critical plane is also shown in this figure The critical plane is perpendicular to the contact area and the LCF crack is predicted to occur on this plane.

Six identical fan discs were then tested in a spin pit test facility to provide basic LCF data for component substantiation. One of the discs was spun to failure after developing a fatigue crack. The remaining five discs were removed from the pit after they had developed large fatigue cracks. During the test cycles, all discs were inspected using Fluorescent Penetrant Inspection (FPI) techniques. The reliable resolution of this method was rather poor due to the difficulties involved in reaching the crack locations for proper inspection. Hence, the cracked areas were brocken open to reveal the crack surfaces and also to count number of fatigue striations (or measure striation spacings) along the crack depth. A typical fatigue crack and fatigue striations is shown in Fig.5. All cracks were associated with multi - origin sites. Metallurgical examination of the microstructure at the crack sites did not reveal any abnormalities associated with the crack initiation and growth. The LCF cracks occured very close to the critical location predicted by the stress analysis procedure (Fig. 4) The results of the striation count test are depicted in Fig. 6. They were used to estimate the number of spin pit cycles, that were incurred during the crack initiation or crack incubation period as well as cycles to grow these cracks to 800 μm (1/32") surface length, as given in Table 1.

In view of the SLA design criterion requirements, the N_c lives estimated by striation counting process were analyzed using Weibull distributions, in order to obtain a 99.9 % reliable (B_{01}) LCF life. The minimum safe life, as shown in Fig. 7, was found to be 4050 spin pit cycles.

2.2 CRACK GROWTH LIFE ANALYSIS

Accurate assessment of the crack growth lives of material bodies strongly depends on the evaluation of the structural response under loads and environment Thermal, dynamic and finite element stress analyses under engine operating and mission profiles are required to define the cyclic load spectrums during repeated mission. Engine alloys need to be characterized in terms of their crack growth properties, fracture toughness and microstructural aspects under isothermal and thermomechanical test conditions.

Recent advances in the field of Linear Elastic Fracture Mechanics (LEFM) has provided closed form solutions for stress intensity factors as a measure of the crack driving energy for a variety of crack types that are experienced in many engineering applications (see for example Refs. 3-6) In this context, Stress Intensity Factor (SIF) formulae of Newman and Raju [3] together with crack closure models have been incorporated into an in - house fracture mechanics procedure [7] in order to assess crack growth lives of gas turbine engine components The general form of the SIF is given in [3] and its application to some P&WC engine components has been discussed in previous works [8,9].

An overview of the crack growth life prediction system used at Pratt & Whitney is shown in the flowchart of Fig 8. The required information for carrying out an analysis is primarily the size and geometry of the initial crack, stress / thermal fields dominating the crack growth and material crack growth properties. These properties are obtained from specimen and sub-component tests, which are usually cut out from actual components and/or their forgings The test data are stored in a storage / retrieval system with built-in crack growth models to account for influence of stress ratios, temperature, frequency, etc. , and hence produce a material database. Some of these crack growth models have already been presented in [1] The stresses are generally obtained from elasto-plastic finite element stress analysis procedures. Stresses that are calculated elastically are shakendown to their corresponding elasto-plastic levels in a pre-processing scheme, using a modified Neuber - Ramberg - Osgood approach. At the present time, two methods for calculation of stress intensity factors are being used and evaluated for application to P&WC engine hardware. In the first method, SIF formulae are used. The second method is based on influence functions and is available commercially [10] In these methods, stresses can be given for a block of load transients representing a loading event (mission) Then partitioning models are used to define elemental load transients. In the end, stress intensity factor solutions and material properties are used to integrate crack growth under these load transients The result of the analysis is crack growth (as a measure of the incurred damage) as a function of loading event count In the present work, fracture mechanics analysis of the fan disc has been carried out under two assumptions of the initial flaw size. These are ·

1. Semi - circular surface crack with an initial surface length of 800 μm (1/32 ") The result of this analysis is superimposed onto the probabilistic life as obtained by the conventio‹ al SLA approach as shown in Fig 9.

2 Semi -circular surface crack with an initial surface length of 250 μm (0 010") This flaw size is assumed to be the capability of an arbitrary Non - Destructive Inspection (NDI) technique. In this case, similar to Damage Tolerance Design (DTD) approach, the safety limit of the fan disc is established as shown in Fig 10.

.hould be noted that Figs. 9 and 10 indicate crack depth growth versus number of spin pit cycles. In both figures, spin pit data points are als. hown for comparison with the predicted lives It may be useful to mention that in earlier investigations [1,8], a Pseudo - Initial - Flaw (PIF) as obtained for the present fan disc. This flaw was based on the statistical analysis of the initial flaws, that were correlated with the spin pit data of individual discs. The PIF was found to be a 25 μm (0.001") long semi - circular surface crack. The crack growth curve corresponding to this flaw is also shown in Fig. 11.

3. DISCUSSION AND CONCLUSION

It can be seen from the block diagram of Fig. 1, that an effective life management in terms of ensuring the structural integrity of engines and exploitation of their usefull safe lives, depends strongly on the following items:

- Accuracy of analytical methods used to predict component behaviour and basic lives.
- Definition and analysis of mission profiles.
- Design substantiation tests.
- Design criteria.
- Material characterization / database.

Application of Damage Tolerance Design philosophy would require additional technology areas such as Non - Destructive - Inspection, design verification test programs, etc. as described for example in [11]. Regardless of the type of the design philosophy used, there exists a lack of knowledge on the crack incubation period and short crack growth, which in many cases appear to be the major portion of the usefull life. The titanium alloy forgings used in the present case have exhibited long crack incubation and short crack growth in a range of 50 - 75 % of the total life The latter period could have been a few times prolonged by shot peening the critical surfaces. More realistic lifing of critical parts also depend on the design criteria. The conventional design criterion at P&WC is based on the 1/1000 probability of formation of a 800 μm (1/32 inches) surface crack. Crack growth analyses are also carried out for further examination of the statistical safe life as shown in Fig. 9. For this purpose, the remaining life beyond the 800 μm surface crack and the value of stress intensity factor at the crack tip are studied in order to ensure that adequate life margin beyond this point exists. In such cases, analytical tools are calibrated for the material and the component on the basis of test and field experience and observation of actual cracks. The crack growth life is then based on the assumption that the 800 μm surface crack already exists in the critical location. Thus, the above life is only applicable to one in a thousand components

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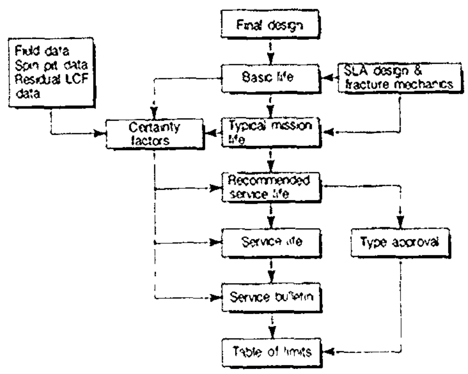
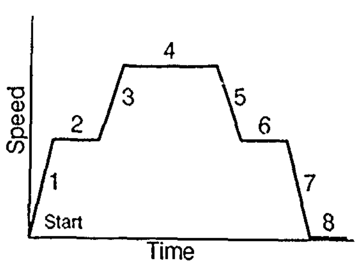
DISC	ACTUAL ACCUMULATED CYCLES				FINAL CRACK SIZE		
	N_i	N_c	N_g	N_t	DEPTH (a) mm	length (2c) mm	a/c
1	-	29,525	11,721	41,246	6.274	-	-
2	35,800	36,400	6,362	42,762	3.302	9.144	0.72
3	25,904	26,704	7,477	34,181	2.614	8.128	0.64
4*	20,687	22,387	10,743	33,130	6 477	12.954	1.00
5	13,183	14,583	12,012	26,596	4.572	11.176	0 82
6	24,595	25,995	5,000	30,995	1.565	3.647	0 84

* :spun to failure
N_i :cycles to crack incubation
N_c :no. of cycles to grow crack to 0 8mm surface length
N_g :cycles to grow crack from 0 8mm to the final size
N_t :total accumulated cycles

TABLE 1: SPIN PIT TEST & STRIATION COUNT DATA OF A FAN HUB CONFIGURATION

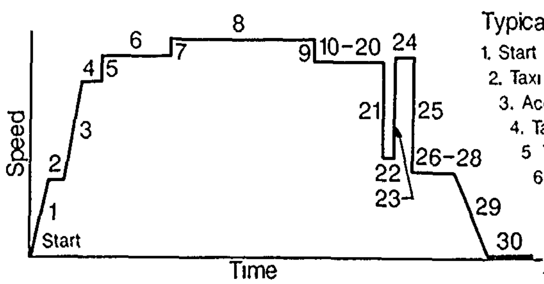
Fig 1 BLOCK DIAGRAM OF THE LIFE MANAGEMENT PROCESS





Basic Cycle

1. Start to idle.
2. Idle
3. Accelerate to maximum
4. Maximum
5. Maximum to idle.
6. Idle
7. Decelerate to shutdown.
8. Shutdown



Typical (And Specific) Mission

1. Start
2. Taxi at ground idle.
3. Accelerate to take-off.
4. Take-off
5. Take-off to climb.
6. Climb
7. Climb to cruise.
8. cruise
9. Cruise to descent.
10-20. Repetative descents, holds & flare.
21. Flare to touch-down.
22. Touch-down
23. Touch-down to reverse.
24. Thrust reverse.
25. Reverse to roll.
26. Roll
27. Roll to taxi.
28. Taxi at idle.
29. Decelerate to shut-down.
30. Shut-down

Fig 2 SCHEMATICS OF TYPICAL BASIC CYCLE & TYPICAL MISSION

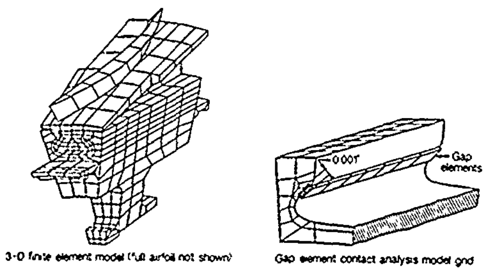


Fig 3 3-D FINITE ELEMENT & BLADE/DISC ATTACHMENT CONTACT ANALYSIS MODELLING

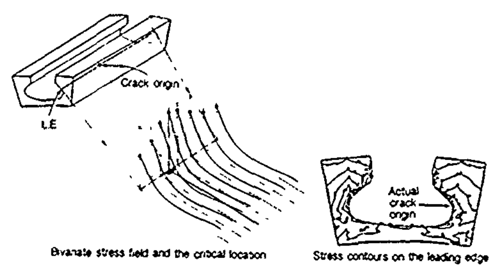


Fig 4 STRESS ANALYSIS & BLADE/DISC ATTACHMENT CONTACT ANALYSIS INDICATING THE LOCATION OF PEAK STRESSES

a) Crack geometry

b) Typical LCF striations

Fig.5 TYPICAL LCF CRACK DEVELOPED IN A FAN HUB

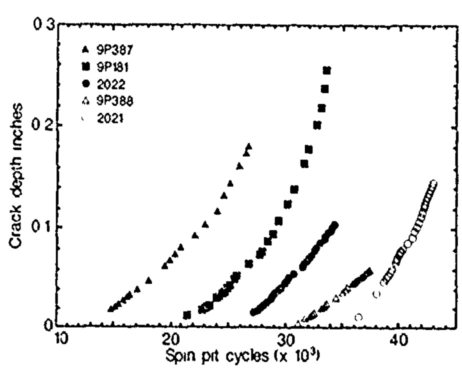


Fig 6 STRIATION COUNT DATA OF FIVE NEW DISCS, WHICH DEVELOPED CRACKS IN THE SPIN PIT TEST

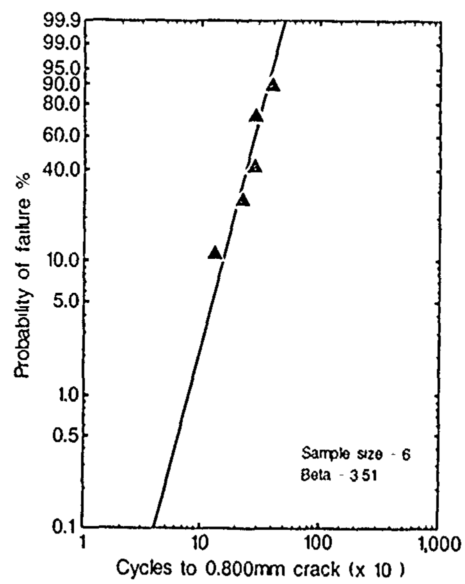


Fig 7 WEIBULL STATISTICAL ANALYSIS OF THE FAN HUB LCF DATA

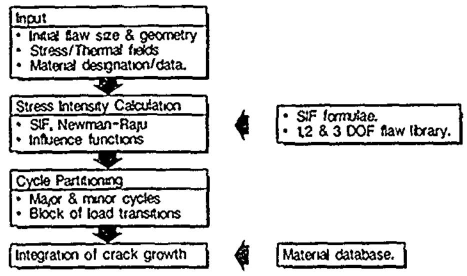


Fig.8 OVERVIEW FLOWCHART OF THE FRACTURE MECHANICS LIFE PREDICTION ANALYSIS SYSTEM AT P&WC

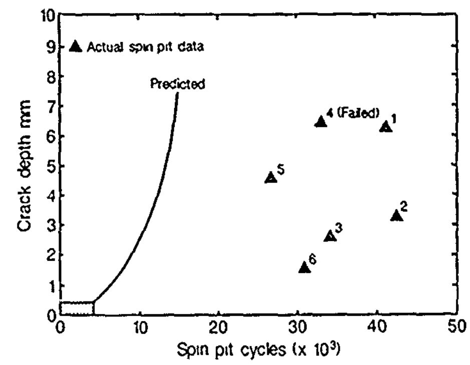


Fig 9 PREDICTED CRACK GROWTH BASED ON A 0.800MM INITIAL FLAW

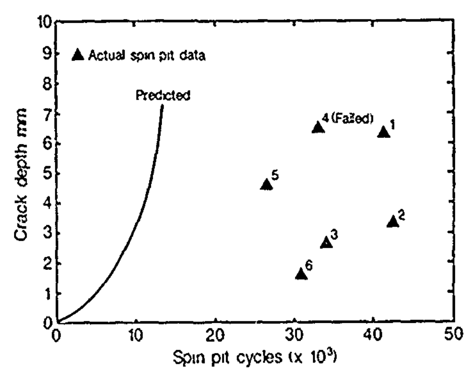


Fig 10 PREDICTED CRACK GROWTH BASED ON A 0.250MM INITIAL FLAW

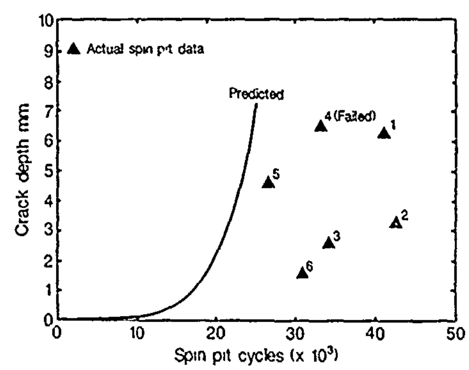


Fig 11 PREDICTED CRACK GROWTH BASED ON A 0.025MM PSEUDO INITIAL FLAW

COMPONENT BEHAVIOUR AND LIFE MANAGEMENT: THE NEED FOR COMMON AGARD APPROACHES AND ACTIONS

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1. INTRODUCTION

All AGARD members:

* Purchase engine
* Run engines
* Repair and overhaul engines
* Investigate Failures

In addition, many AGARD members build aero-engines, either as prime contractors or sub-contractors. Gas turbine engines are thus an International produce that requires a co-ordinated approach and outlook on:

* Research and development
* Design, certification and lifing
* Usage recording and life management

Without such co-ordination, manufacturer and customer will have to use many different specifications and to meet varying certification regulations. This will add to costs and waste resources.

Four specific areas where a commonality of approach might be of benefit are:

* Life prediction
* Component testing
* Accelerated mission testing

2. LIFE PREDICTION

In order to compare existing life predictive methods, and to develop new and improved approaches, it is essential to establish a number of test cases. These can then serve as bench marks against which Industry and Research Laboratories can evaluate their models. This is the approach being adopted by the AGARD Propulsion and Energetics Panel. For the PEP programme to be a success, certain minimum information must be made available for each test case:

* Component geometry, including dimensions and tolerances
* General machining and processing information for critical parts
* Engine usage monitoring data
* Definition of boundary conditions for stress analysis
* Heat transfer information or time - temperature profiles
* Basic material data for critical components and adjacent hardware
* Field experience for the component

To-date five possible test cases have been considered and two have been identified as having potential for life assessment trials. Other test cases are being sought.

In general the problems encountered have been:

* The quantity of data required for a test case
* The willingness of Companies to release databases and other proprietary information (NB: a database can cost $2M)
* Up front costs to the originator of test case preparation and the cost to all participants of running the test cases
* The need to balance contributions and to release data on an equitable basis.

This PEP activity should therefore be of particular interest and relevance in the context of the SMP worshop series, and should provide a vehicle where SMP technolgies to be tested.

3. COMPONENT TESTING

Damage Tolerant Design places great emphasis on specimen testing to provide the database for disc design and lifting. Such specimens can be "simple", such as the traditional LCF and CT testpieces, or "complex". Complex specimens can either model features seen in discs, or be cut from actual discs and contain representative surface finishes.

Fracture mechanics design and lifting algorithms are currently validated for simple laboratory specimens. In applying such algorithms to actual components a number of assumptions have to be made concerning a range of issues such as; complex geometries, stress fields, loading cycles.

To use a damage tolerant design approach safely thus requires:

* Generic research to quantify assumptions
* Validation via component testing.

These workshops have demonstrated a need for an increased understanding in a number of materials related areas if the maximum information is to be gained from component testing. In particular, a larger generic research base is required on:

* Small crack growth behaviour and modelling
* Effect of mission cycling
* Statistics of fracture mechanics and NDE
* Internal stress prediction and modelling

These are all areas where AGARD SMP can contribute, and where collaborative programmes could assist in achieving the goal.

In the wider context of actual disc lifing, there is a need for all AGARD members to speak with a common voice in order to: Satisfy Certification Authorities. Act as intelligent customers. Obtain value for money. Before this can be achieved there is a need to reach agreement on a number of technical issues, including:

* Damage algorithsm
* Stress and Thermal algorithms
* Statistical approaches
* Acceptability of databases
* Interpretation of results
* Relationship between rig tests and actual engine operation.

The first two items can be approached through objective programmes comparing different algorithms against agreed test cases. These AGARD SMP workshops have demonstrated that the latter items are more subjective, require further debate, and that short term agreement will be more difficult to achieve.

4. ACCELERATED MISSION TESTING

Accelerated mission testing has traditionally been seen as a method of checking engine performance and reliability. It has not been part of the disc lifing or safety strategy, being directed mainly at creep limited hot end components that cannot be LCF lifed. In order to accelerate the cycle, dwell times at low temperature are normally removed.

The exact role and function of accelerated mission testing is not always clear, and appears to have a number of different definitions:

USAF MIL STD 1783 - AMT

"An Accelerated Mission Test shall be performed..... The test run schedule shall simulate the Design Duty Cycle".

UK MILITARY SPEC - ASMET

"Hot end component mission simulation.......ie: blades, combustion chambers and non-critical parts".

US NAVY MIL SPEC E-005007E - ASMET

"Hot part damage equivalent to hot parts life mission hours requirement".

"Critical parts LCF damage equivalent to half the cold parts life mission hours requirement".
(discs then spun on for a further half life)

A first action on AGARD members should be to agree on a common definition and interpretation of an accelerated mission test, and on its role and purposes. The need for two separate cycles, directed at hot and cold parts respectively, also merits consideration.

In a damage tolerant design context there appear to be three fundamental problems that need addressing:

* In accelerating the mission the hot parts life is always reached well before the cold/critical parts life.
* To spin on a single disc to the cold parts life is itself of little statistical value.
* No account is usually taken of fracture mechanics cumulative damage rules in arriving at the AMT/ASMET cycle - thus the relevance of the results are open to debate.

These are topics of direct interest to all who purchase engines against specifications.

5. ENGINE USAGE

In any fracture mechanics or damage tolerent design, materials can only be used to their full capability if the exact engine usage is known. Having established how an engine has been used, this information must then be translated through to the temperatures and stresses experienced by each component and feature.

Currently a number of different methods or recording and analysis are adopted by users:

* Manual recording with off line analysis
* Automatic recording with off line analysis
* Automated recording with on board analysis.

Manual recording has inherant problems in that there is a doubtful correlation between what a pilot logs and the actual mission he flies. Automated recording also covers a wide range of levels, from the simple monitoring of throttle openings to recording multi-channel throttle, temperature, RPM data, etc.

Two steps are required in order to translate this into "damage":

* Algorithms/Methods to go from the complex mission cycle to a simplified cycle for subsequent analysis of damage.
* Methodologies to go from the resulting cycle and temperature information to damage imposed on a component or feature.

If engine usage monitors and LCF counters are to be fitted, and the results incorporated into lifing calculations, it is essential that:

* They all give the same result for the same mission
* They use algorithms relevant to fracture mechanics and DTD
* Users in all Countries believe the results.

This can only be achieved through collaboration and exchange of ideas, methods and equipment - an area where AGARD activity could help at all levels.

6. CONCLUSIONS

Component Behaviour and Life Management are central to Damage Tolerant Design and Engine Certification.

With an "International Product" such as the Gas Turbine Engine there is a need for Laboratories in the various Countries to be able to believe each others data, results and explanations. This will enable NATO Air Forces to purchase, maintain and fly modern engines using new lifing methods, materials and manufacturing processes with confidence and in safety.

In particular:

(1) All AGARD Countries are customers and users of gas turbine engines, military and civil, bought from a number of sources.

(2) There is a need to establish a common position if components lifed by DTD are to be introduced and managed in a safe and cost effective manner - and the various Lifing Authorities convinced that the lifing methodologies are safe.

(3) There are a number of materials related areas that would benefit from collaborative activity:

* Materials Testing
  - Small Cracks
  - Mission Cycling
  - Surface Condition
  - Statistics
* Stress Analysis
  - Algorithms
  - Forging modelling
* Damage Rules

AGARD would be a useful and effective forum for such activities.

Damage Tolerance Concepts for Engine Constituents

Workshop III

Component behaviour and life management

RECORDERS REPORT

The topics of the discussions which take place during the Workshop III on Damage Tolerance Concepts for Engine Constituents can be classified as follows :

a - Modelling and Numerical Methods

b - Specific Behaviour of Materials (in particular, with respect to crack growth)

c - Testing

d - Data and parts Management

For each of these points, the discussions led to some points of agreement which are reviewed here.

a - Modelling and Numerical Methods

In this area, the need of validating tools for models and methods has been clearly recognized.

Concerning the Continuum Damage Mechanics, it is suggested to evaluate this approach in random situations, in order to check its ability to predict the statistical distribution of the calculated life-time in presence of a scattering on the input.

In view of comparing the predictive capability of different modelling methods, it is emphasized that such comparisons should be performed using the same database.

b - Specific behaviour of materials

When performing crack growth modelling it is recomanded to take into account the influence of aging, since crack growth behaviour is significantly dependant on this parameter.

For short cracks (i.e of length up to 5 grain sizes) the influence of grain size is of great importance on the crack growth rate, but vanishes quickly as crack length increases.

In connection with crack growth, it is generally observed that the lifetime exhibits a large scattering for cracks up to .4mm long; for longer cracks this scattering is significantly reduced.

It still appears necessary to be able to discriminate between "short crack" and "nucleation (or incubation)" crack growth.

c - Testing

Concerning partial test on bench, two points are raised :

i)- it is observed that they are not often conducted until rupture; consequently the data base is not sufficiently large (in view of life-time assessment) to assure a good statistical value to these results.

ii)- it is desirable to check design methods against partial tests, although it seems rather difficult to have these tests fully representative of all phenomenas included in the analytical or numerical methods; for example, it is not easy to achieve, in partial test, the same balance between creep and thermal fatigue in operational conditions.

Accelerated Mission Testing is considered as a useful tool for detecting gross structural deficiencies but not as a lifing tool, due to the unstabilized conditions for the material (influence of corrosion, for instance, cannot be adequately simulated in this kind of test).

Five levels of testing can be envisaged :

1 - Laboratory tests, to investigate basic properties

2 - Tests on technological specimens for checking stress analysis

3 - Tests on bench, at component level

4 - Tests on engine test bed, to simulate the combination of loads and temperature

5 - Tests in operational conditions

d - Data and parts Management

Although the same type of engine can perform a great variety of missions, which confirms the great interest of monitoring significant parameters, it has been observed a "smoothing" effect due to engine redistribution in the fleet after checks or repairs.

Taking this effect into account allows the definition of an average mission with an associated scatter.

Monitoring of metal temperatures is of particular importance, since, with aging, the same level of performance demands an increase of the temperature.

In view of the reassessment of the potential of repaired parts, a central management of parts is highly desirable.

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14. Abstract

The Structures and Materials Panel is co-ordinating a series of four Workshops planned within the framework of a Review on Damage Tolerance for Engine Structures. The Review aims to address the areas critical to the acceptance of an approach based on damage tolerance concepts as an alternative lifing philosophy to that of "safe-life" for the design of engine components.

Workshops have been held at two previous Panel Meetings dealing with Non-Destructive Evaluation of Components, AGARD R-768 and Defects and Quantitative Materials Behaviour, AGARD R-769.

The third Workshop was held during the sixty eighth Panel Meeting and surveyed current approaches to the prediction of component behaviour and the establishment of suitable inspection schedules. The role of testing and life management planning in these approaches was examined. Future technology requirements and the need for a common AGARD approach were discussed.

This publication includes the presentations made in the course of the third Workshop, together with the Recorders' Report of the discussions.

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